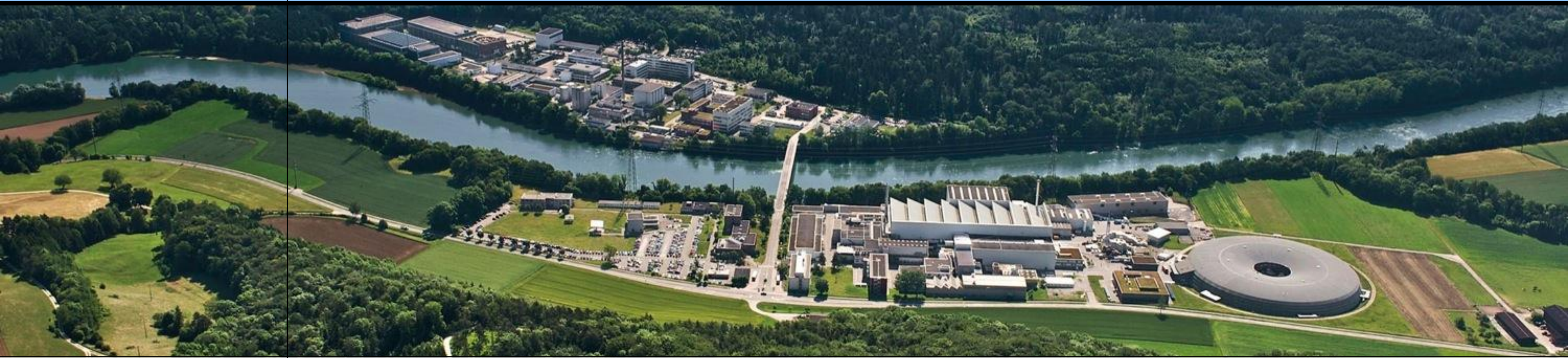
PAUL SCHERRER INSTITUT



Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

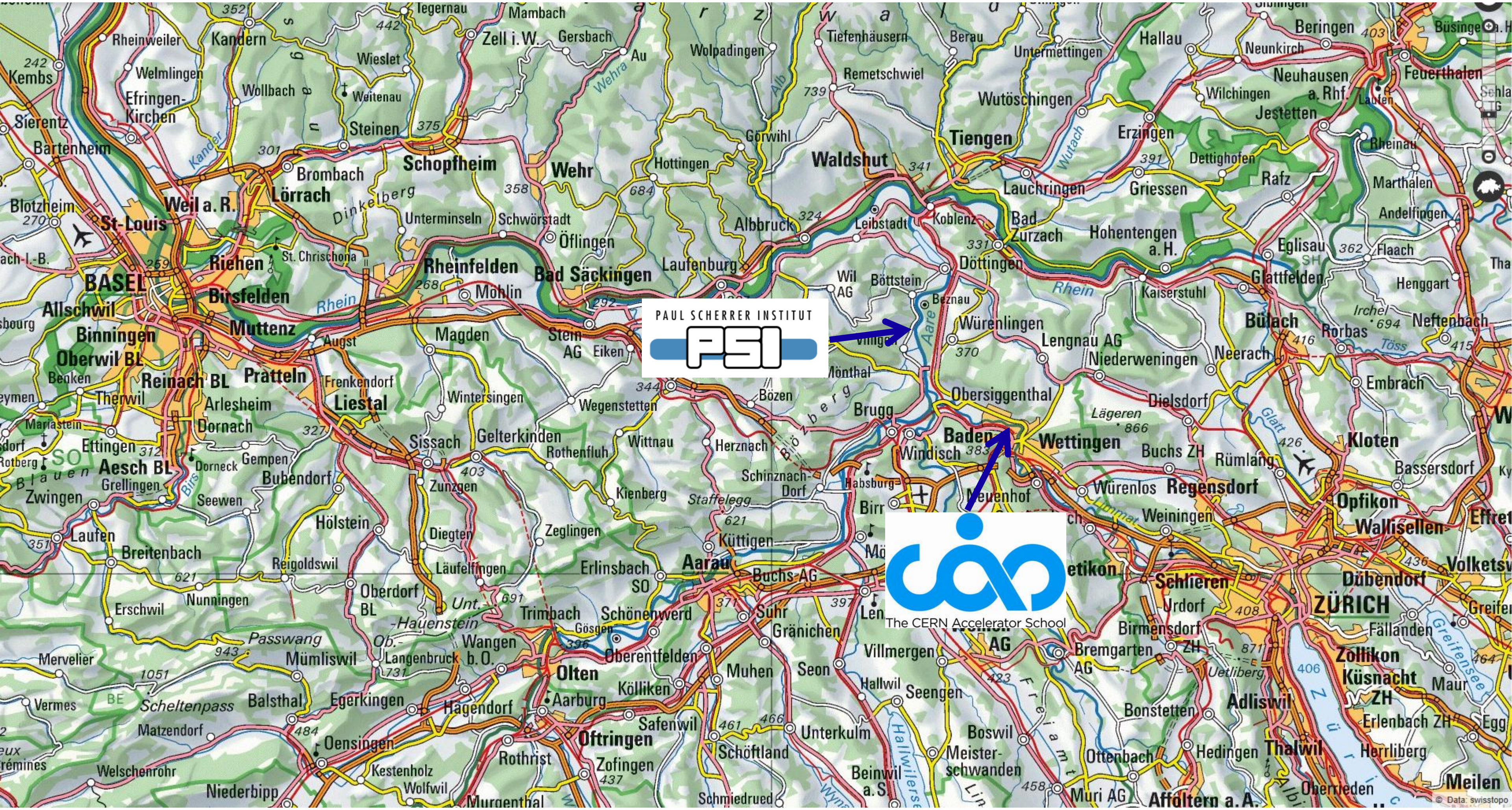
Hans Braun

Swiss FEL, the X-Ray Free Electron Laser at PSI

CAS Baden, 10.5.2014

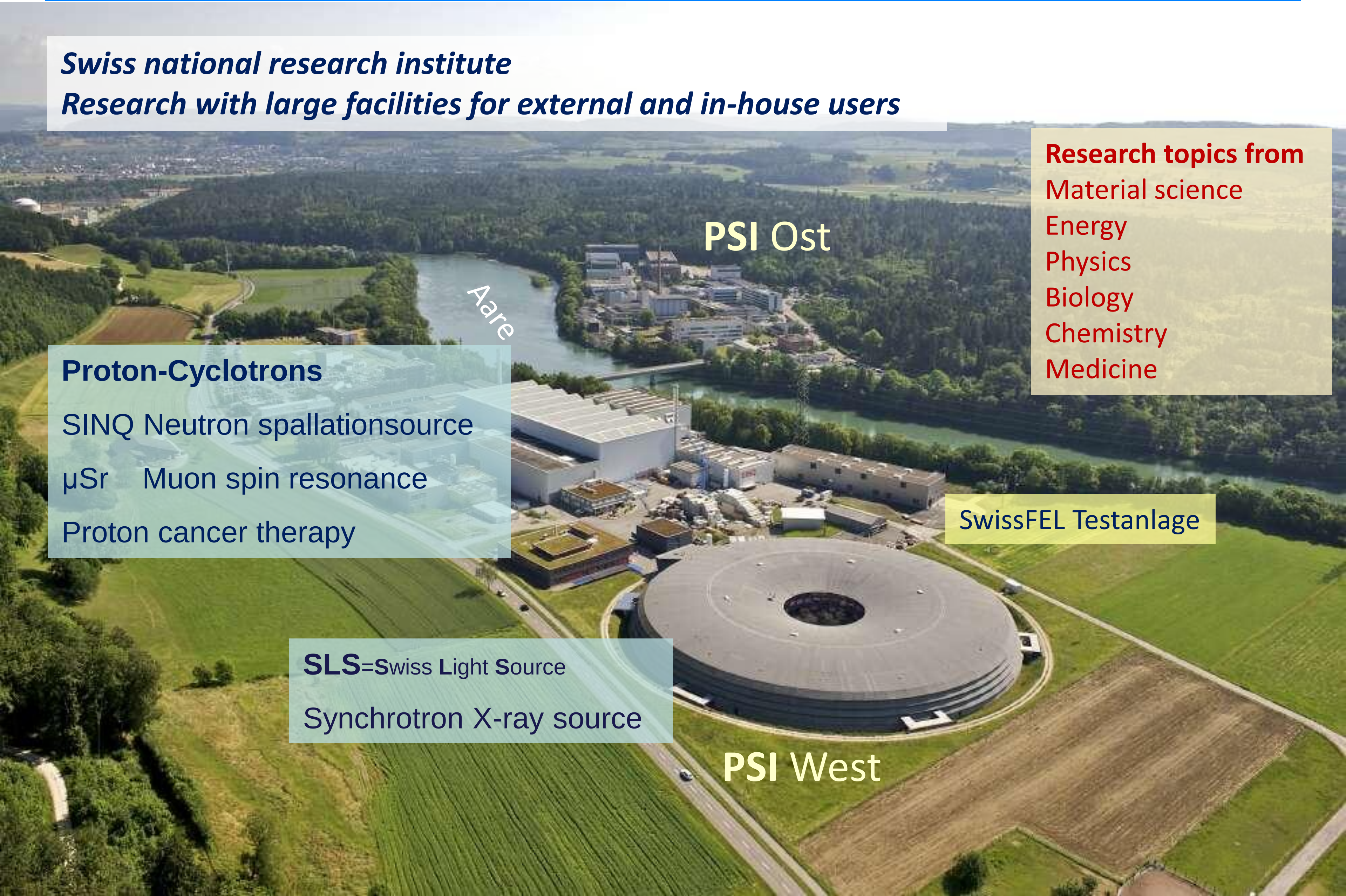
PAUL SCHERRER INSTITUT PSI

Paul Scherrer Institut



Paul Scherrer Institut

Swiss national research institute
Research with large facilities for external and in-house users



Research topics from
- Material science
- Energy
- Physics
- Biology
- Chemistry
- Medicine

Proton-Cyclotrons

SINQ Neutron spallationsource

μSr Muon spin resonance

Proton cancer therapy

SwissFEL Testanlage

SLS=**S**wiss **L**ight **S**ource

Synchrotron X-ray source

Paul Scherrer Institut

Swiss national research institute

Research with large facilities for external and in-house users

Research topics from
- Material science
- Energy
- Physics
- Biology
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Proton-Cyclotrons

SINQ Neutron spallationsource

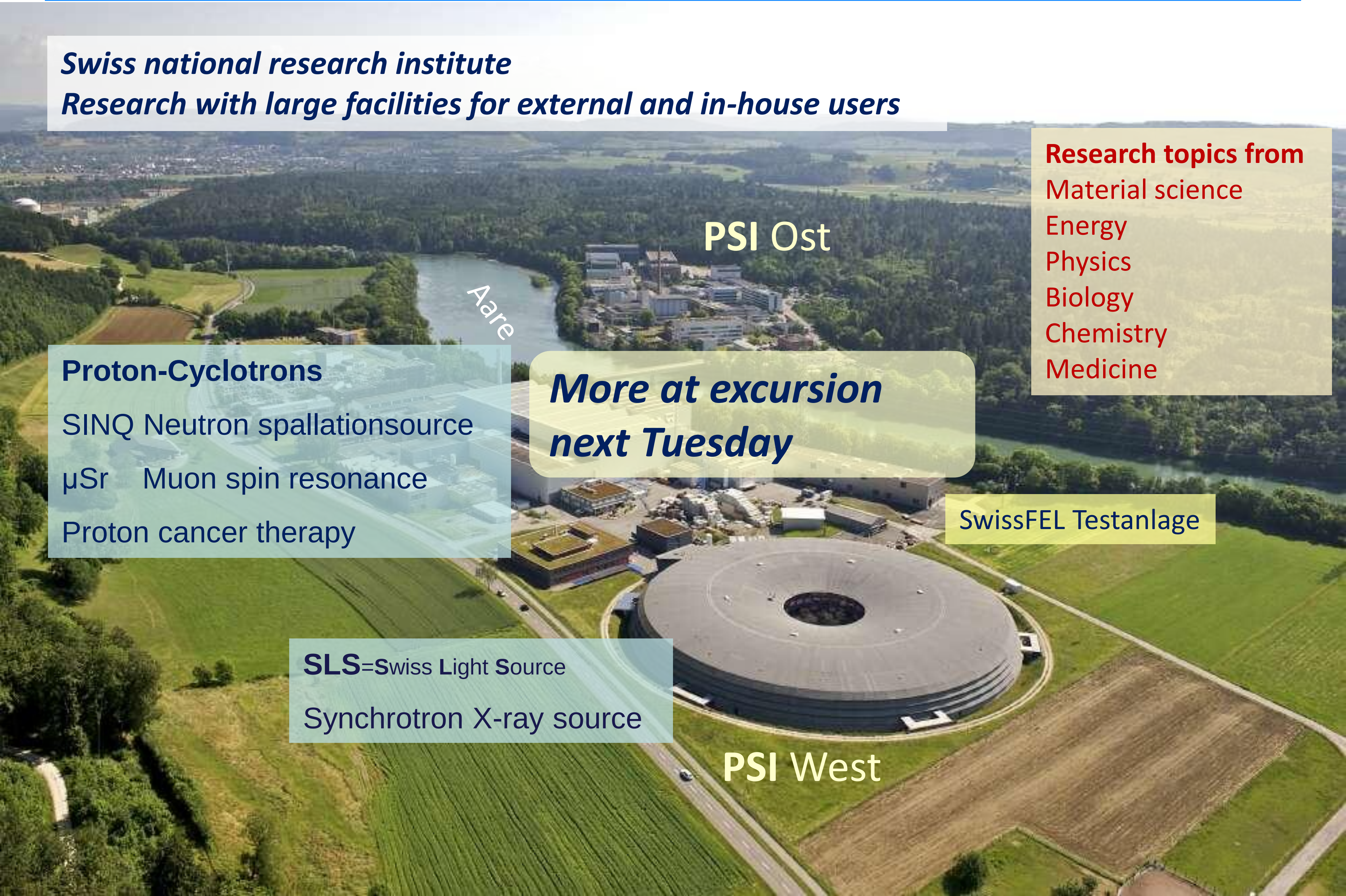
μSr Muon spin resonance

Proton cancer therapy

More at excursion next Tuesday

SLS=**S**wiss **L**ight **S**ource

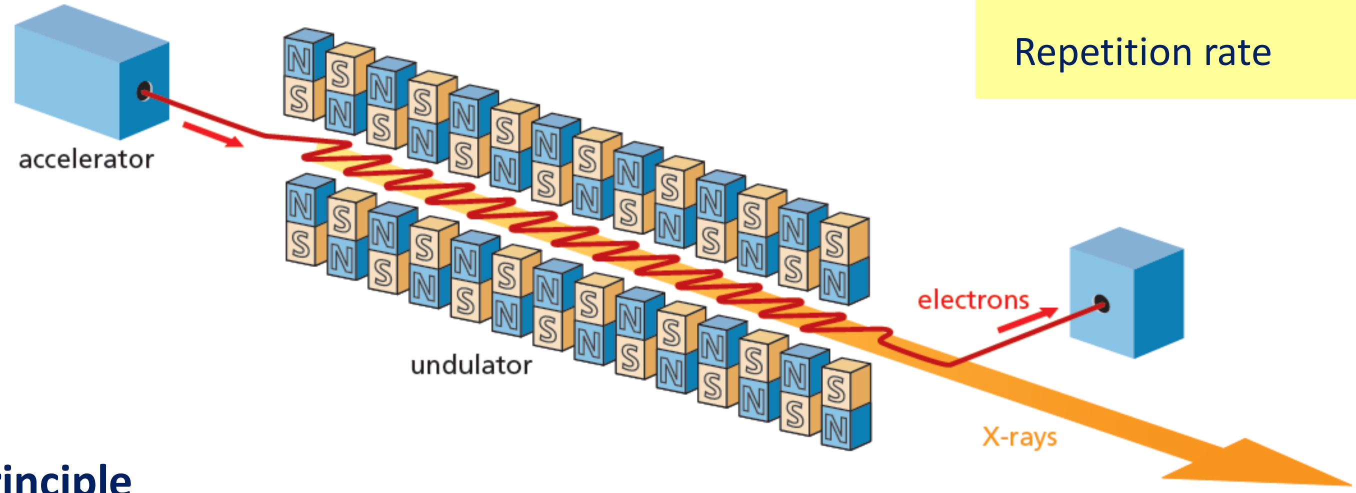
Synchrotron X-ray source



X-ray Free Electron Laser *SwissFEL*
the new large research facility at PSI

SwissFEL parameters

Wavelength from	1 Å - 70 Å
Pulse duration	1 fs - 20 fs
e^- Energy	5.8 GeV
e^- Bunch charge	10-200 pC
Repetition rate	100 Hz

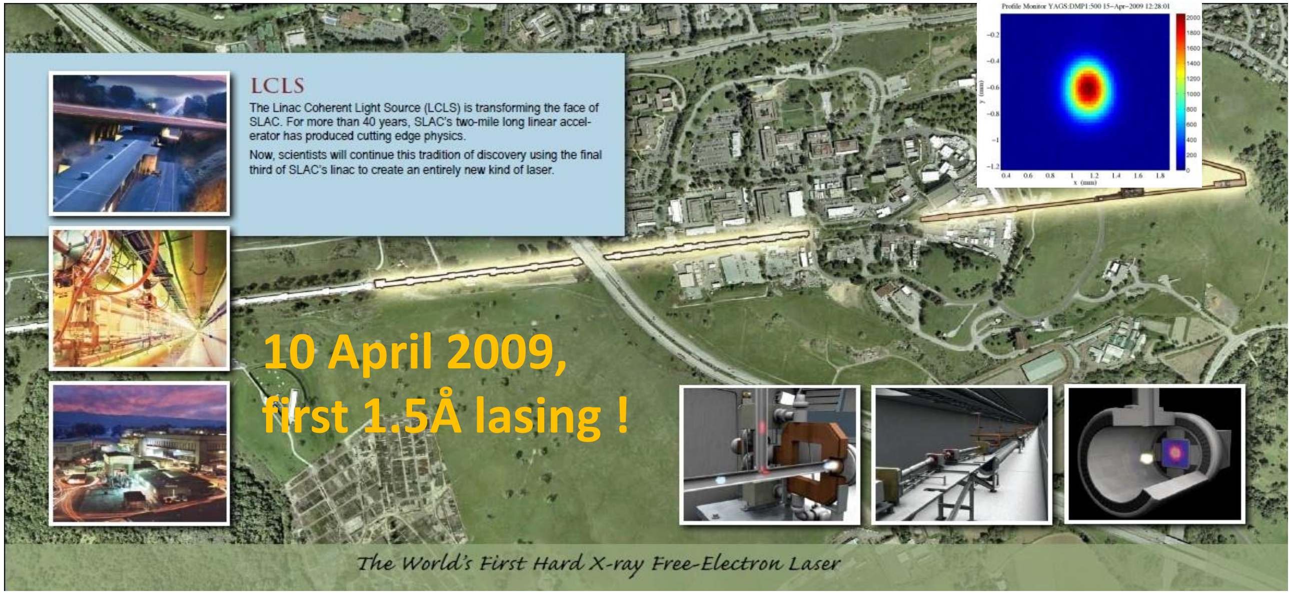


FEL principle

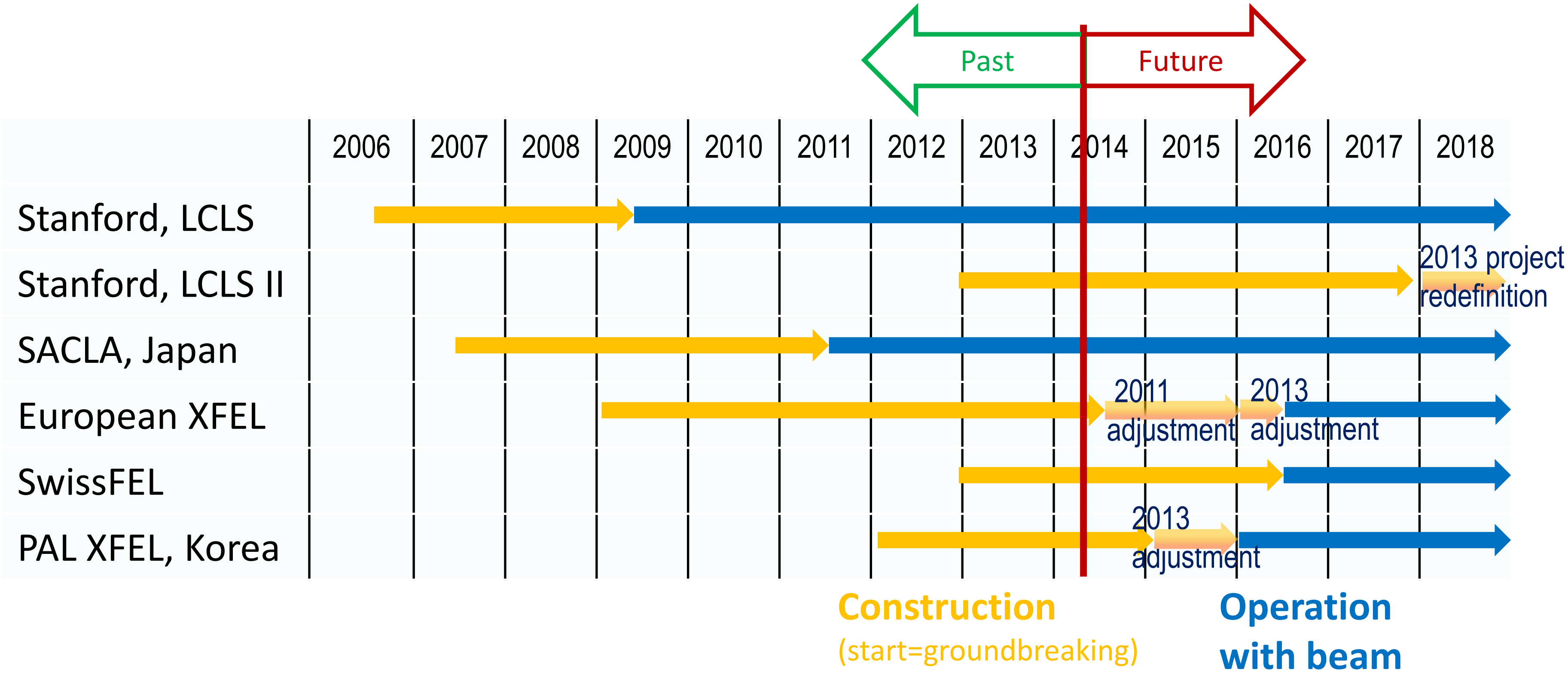
Electrons interact with periodic magnetic field of undulator magnet to build up an extremely short and intense X-ray pulse.

Worldwide two X-ray FELs in operation

15 GeV Electrons **LCLS** 1.5 Å X-Ray
Linac Coherent Light Source



Schedule hard X-ray FELs worldwide



Why X-ray FEL

During Renaissance science starts new concept

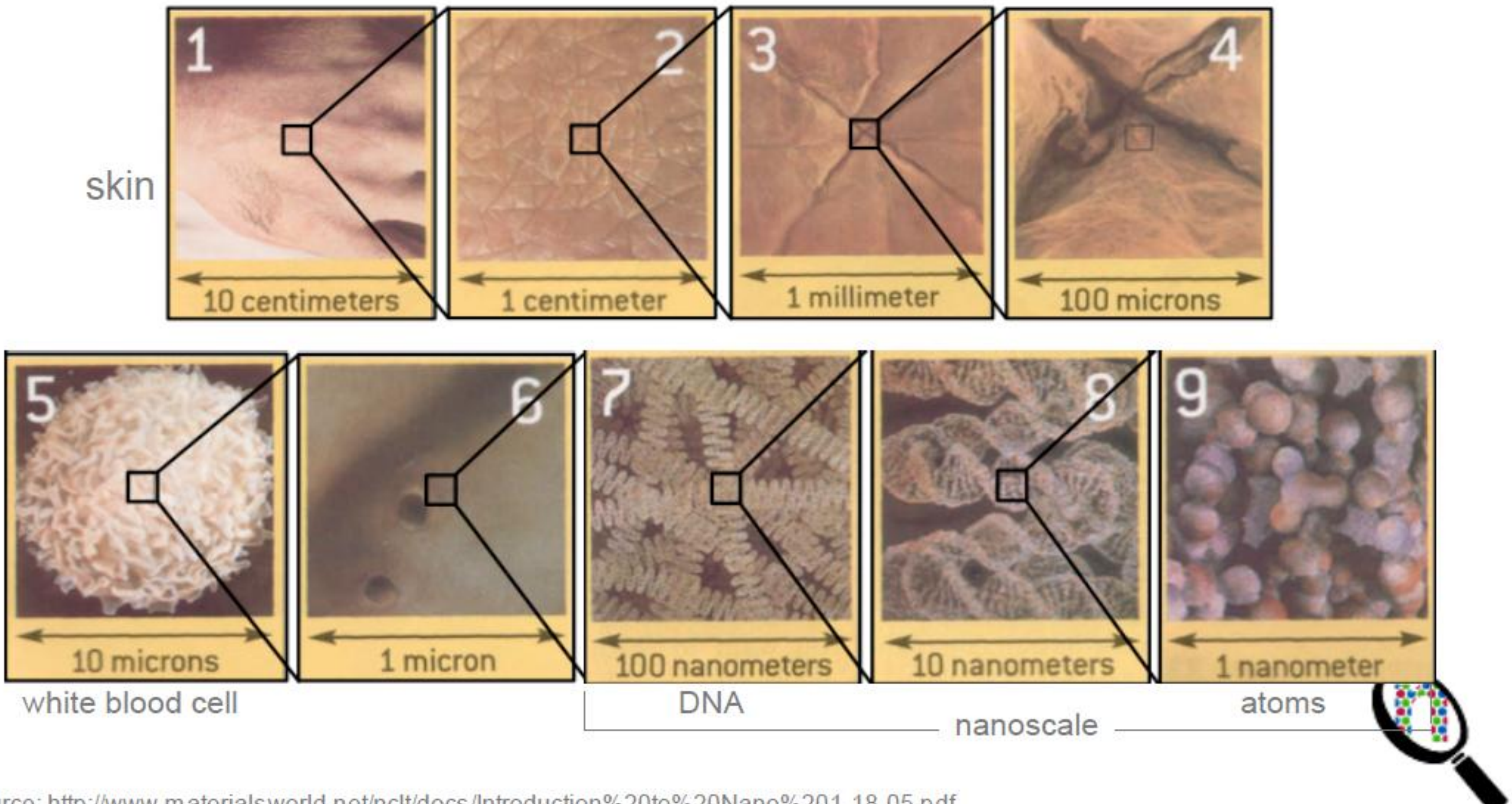
Understand nature by observation of things smaller than what the plain eye can see

Invention of microscope ≈ 1600 a.d.

Why X-ray FEL cont.

How Big is a Nanometer?

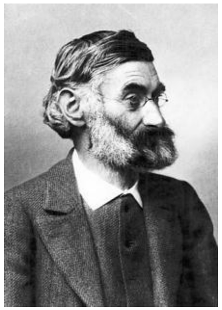
- **Consider a human hand**



Source: http://www.materialsworld.net/nclt/docs/Introduction%20to%20Nano%201-18-05.pdf

X-ray properties revisited

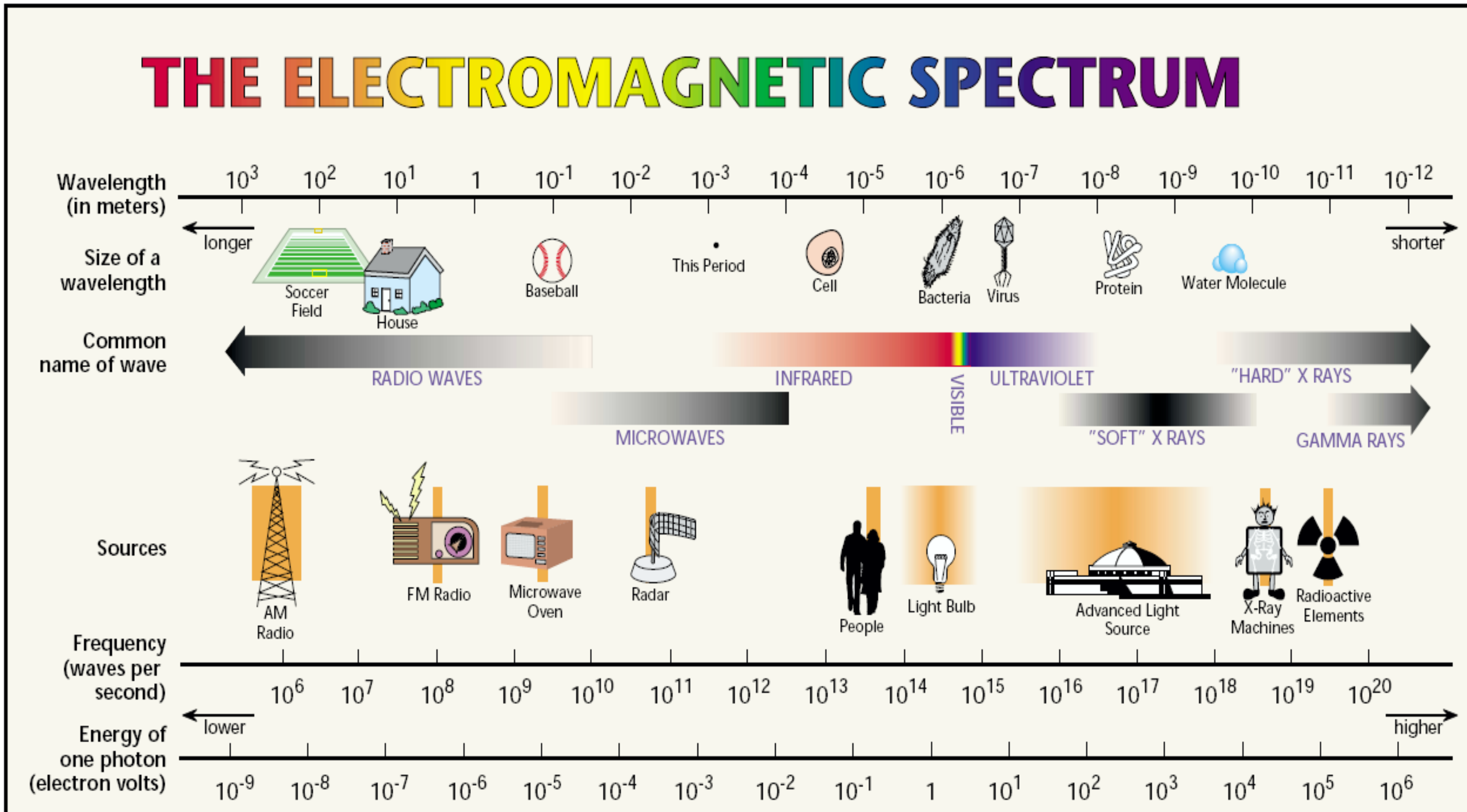
Ernst Abbe
1840-1905



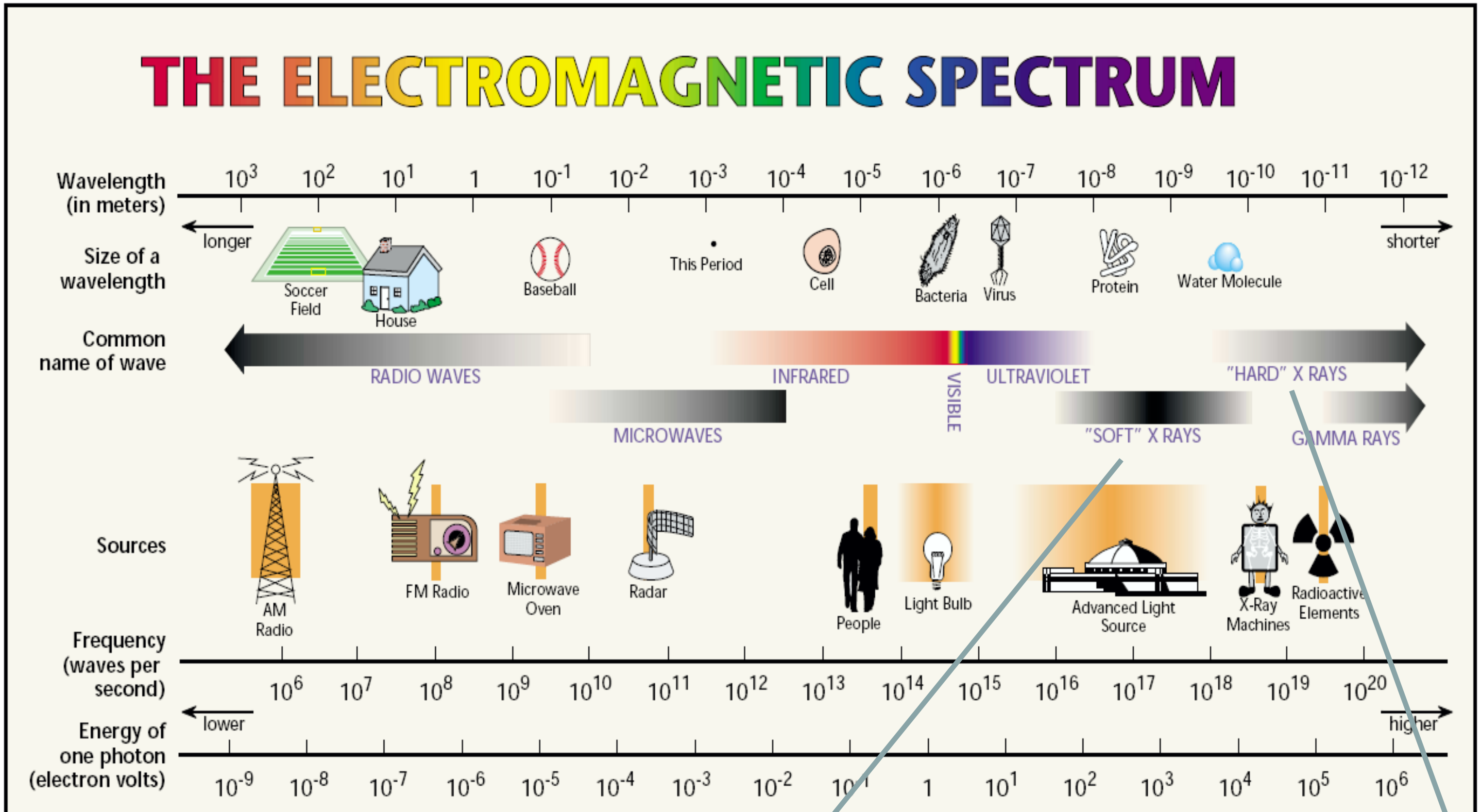
Diffraction limit of microscope

$$d > \frac{\lambda}{2n \sin\theta}$$

⇨ only Objects > 1µm can be imaged with visible light



X-ray properties revisited



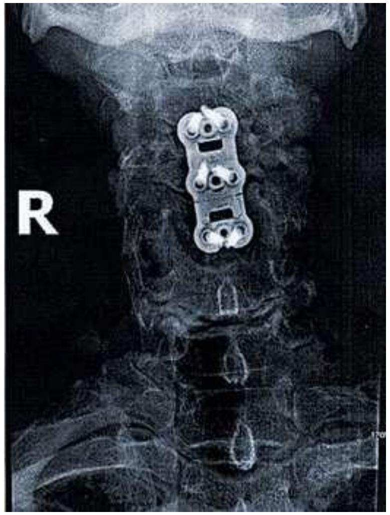
Soft X-rays
typical λ = 1 nm =10Å , 1.2keV

Hard X-rays
typical λ = 0.1nm = 1 Å , 12 keV

⇒ ***X-rays have right wavelength to resolve nanoscale objects***

X-ray properties revisited, cont.

Sylvester Stallone
imaged with visible light

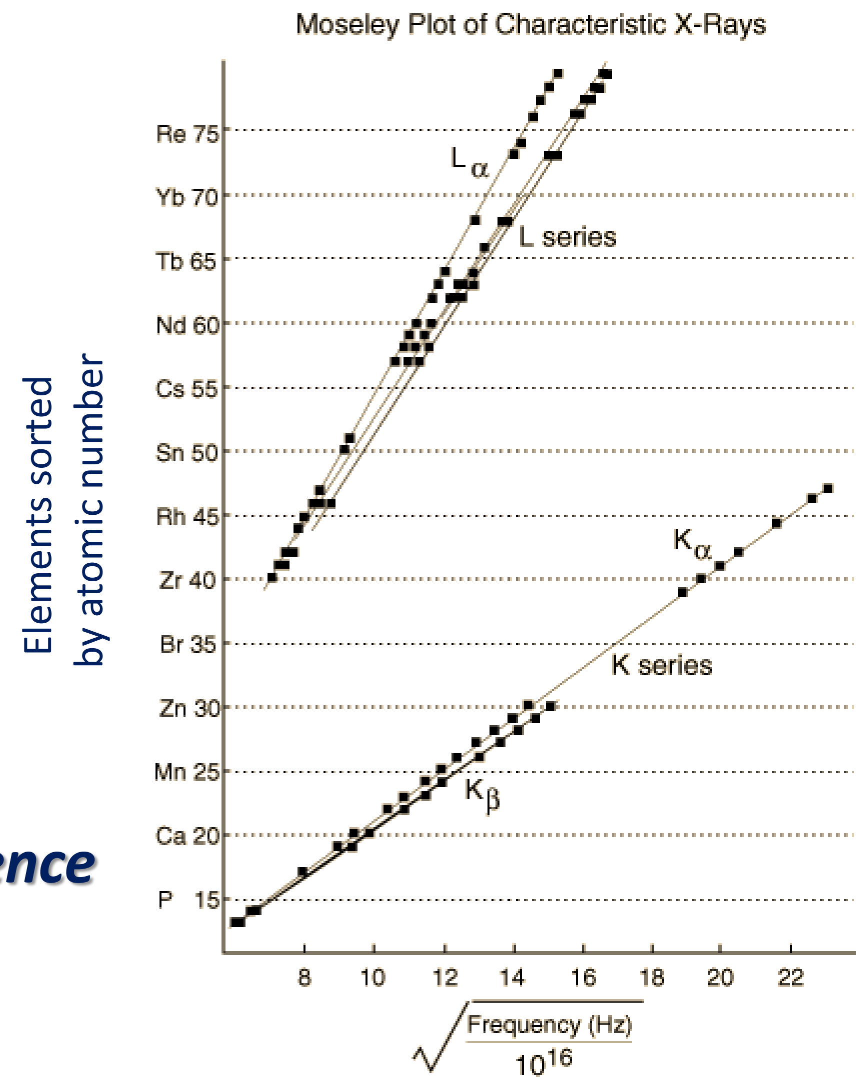


Sylvester Stallone
imaged with X-rays

X-ray attenuation is weak
⇒ extended objects can be imaged in transmission

X-ray properties revisited, cont.

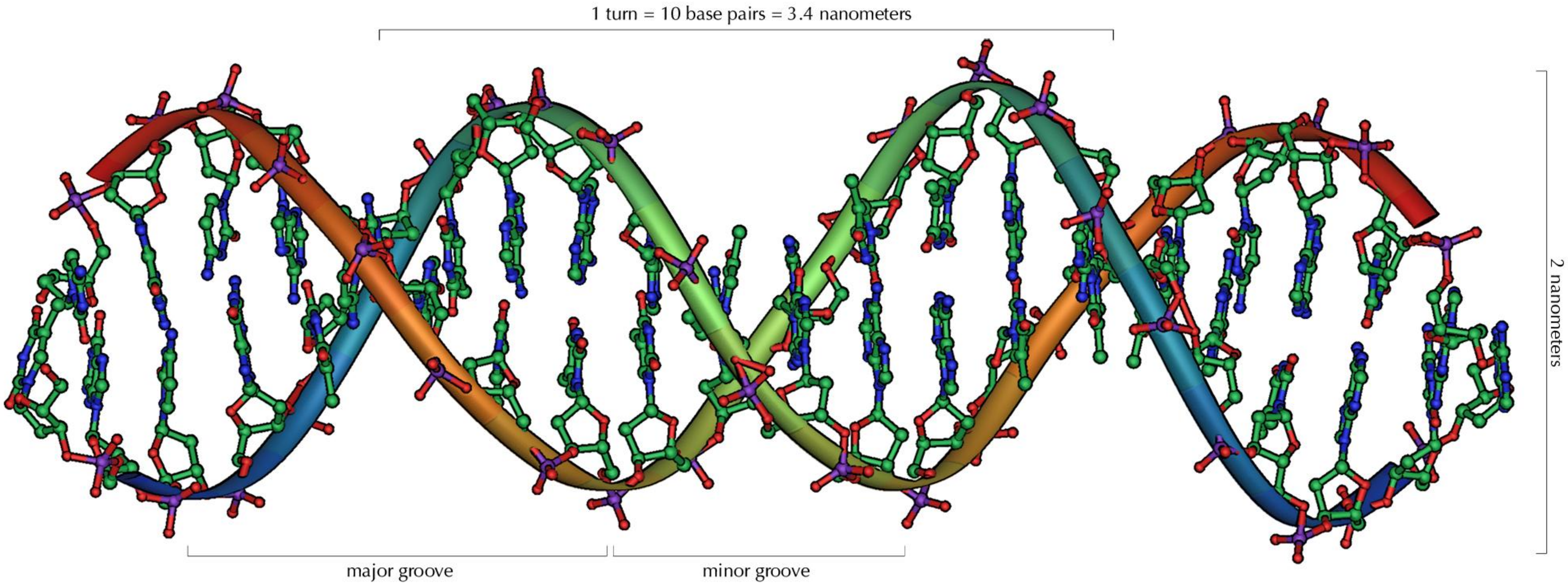
Henry Moseley
(1887 - 1915)

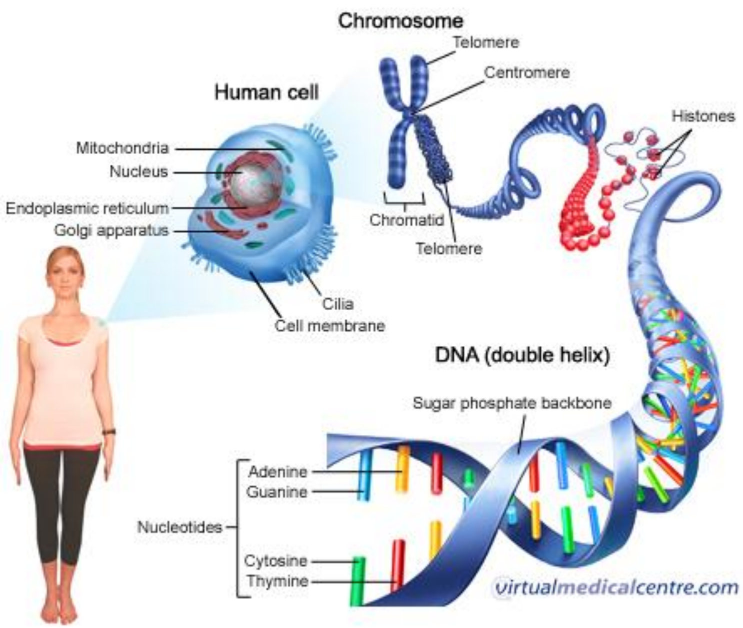


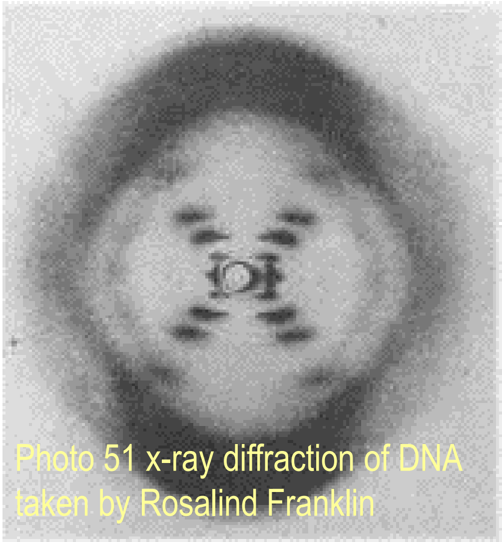
Adapted from Moseley's original data (H. G. J. Moseley, Philos. Mag. (6) 27:703, 1914)

⇒X-rays absorption & fluorescence is element selective

Example of X-ray scattering
Double helix Structure of DNA,Watson & Crick 1953





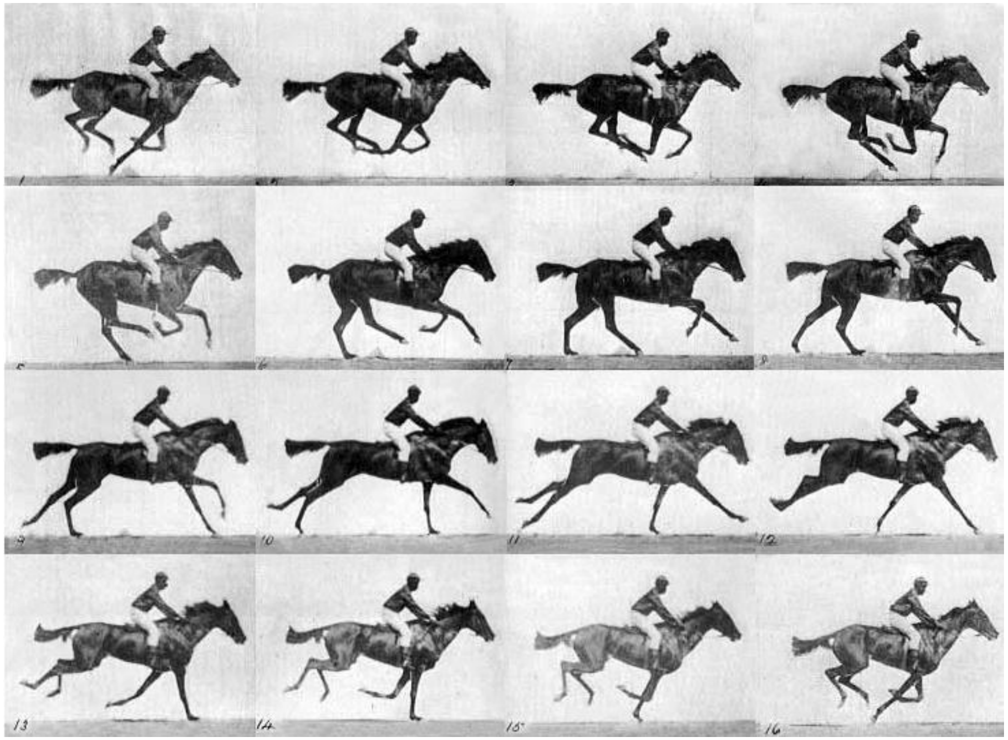


What to do next?

observe structure → observe function

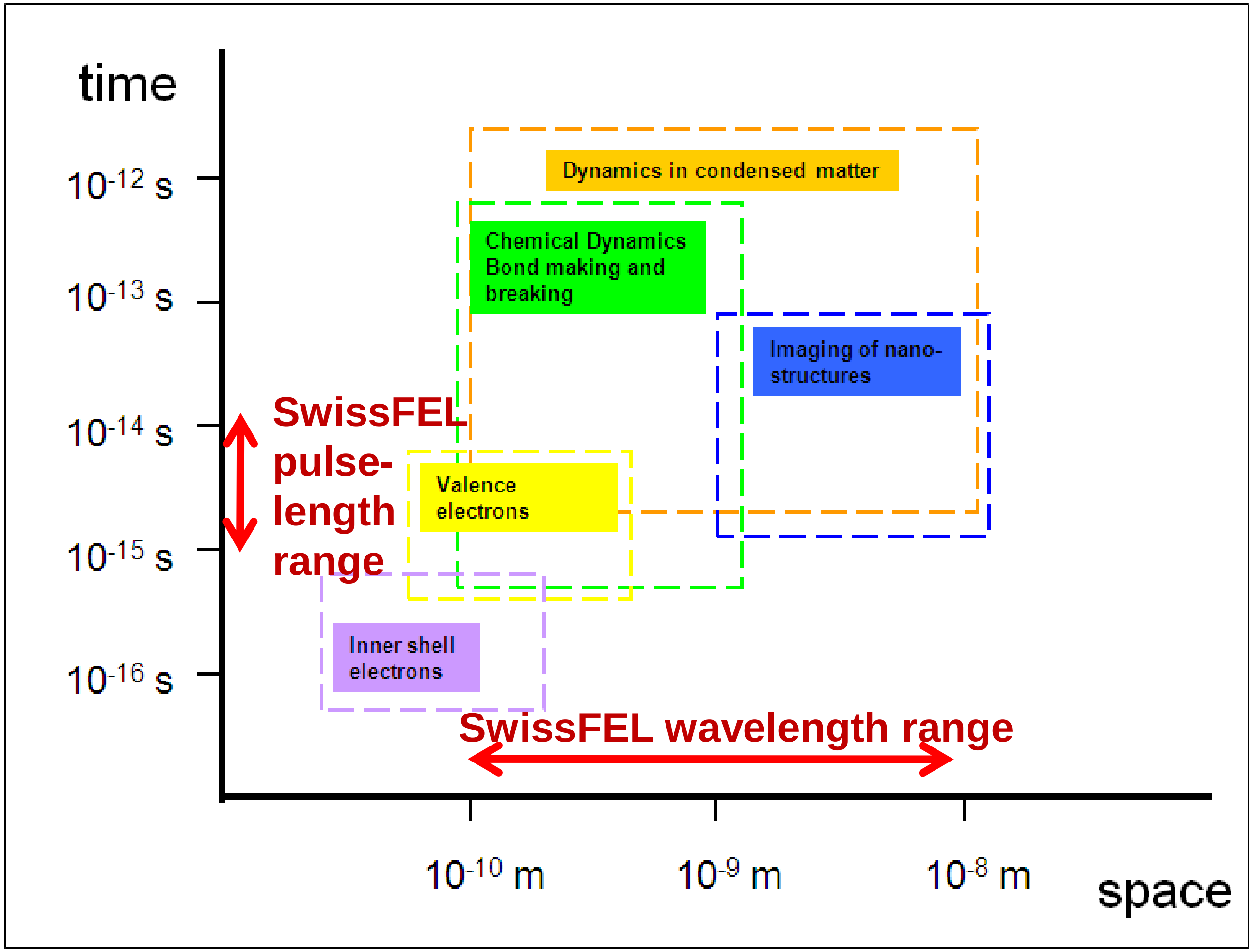
Louis Jacques Mandé Daguerre
Portrait M. Sabatier-Blot,1844

exposure time: few minutes



Eadweard Muybridge
The Horse in Motion, 1872

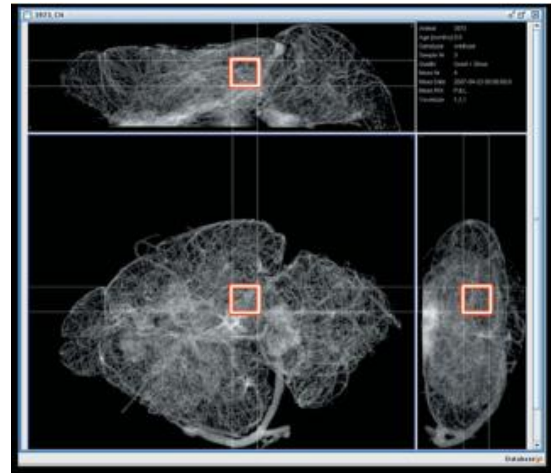
Exposure time: few milliseconds



⇒ X-FEL allows for flash images on time scale of fastest chemical processes

Spiral star cluster

Brain of mouse



Kevin Mader *et al.* • Synchrotron-based tomographic microscopy

J. Synchrotron Rad. (2011). **18**, 117–124

No matter what size of object you observe,
you always need to collect typically about

100 pixel x 100 pixel x 100 photons/pixel = 1.000.000 photons

for a 2D image (better much more)

⇒ smaller objects and finer time resolution require higher flux density
But high flux ⇨ radiation damage

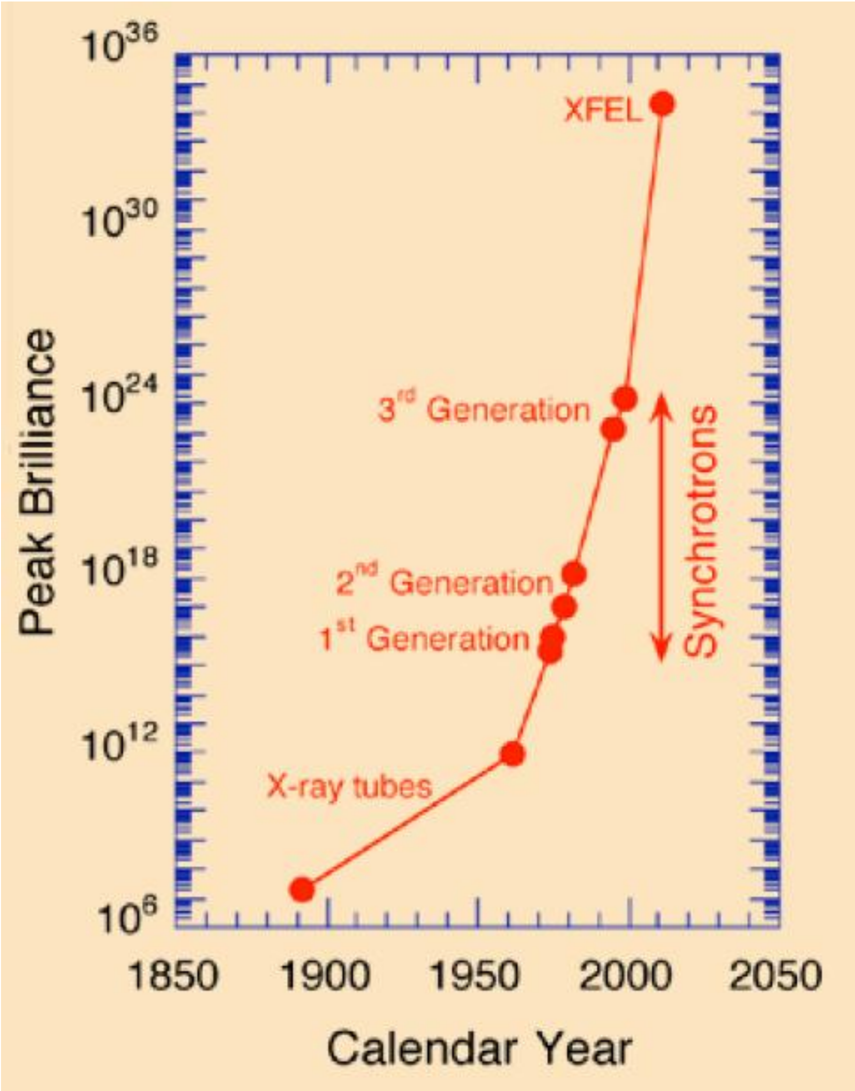
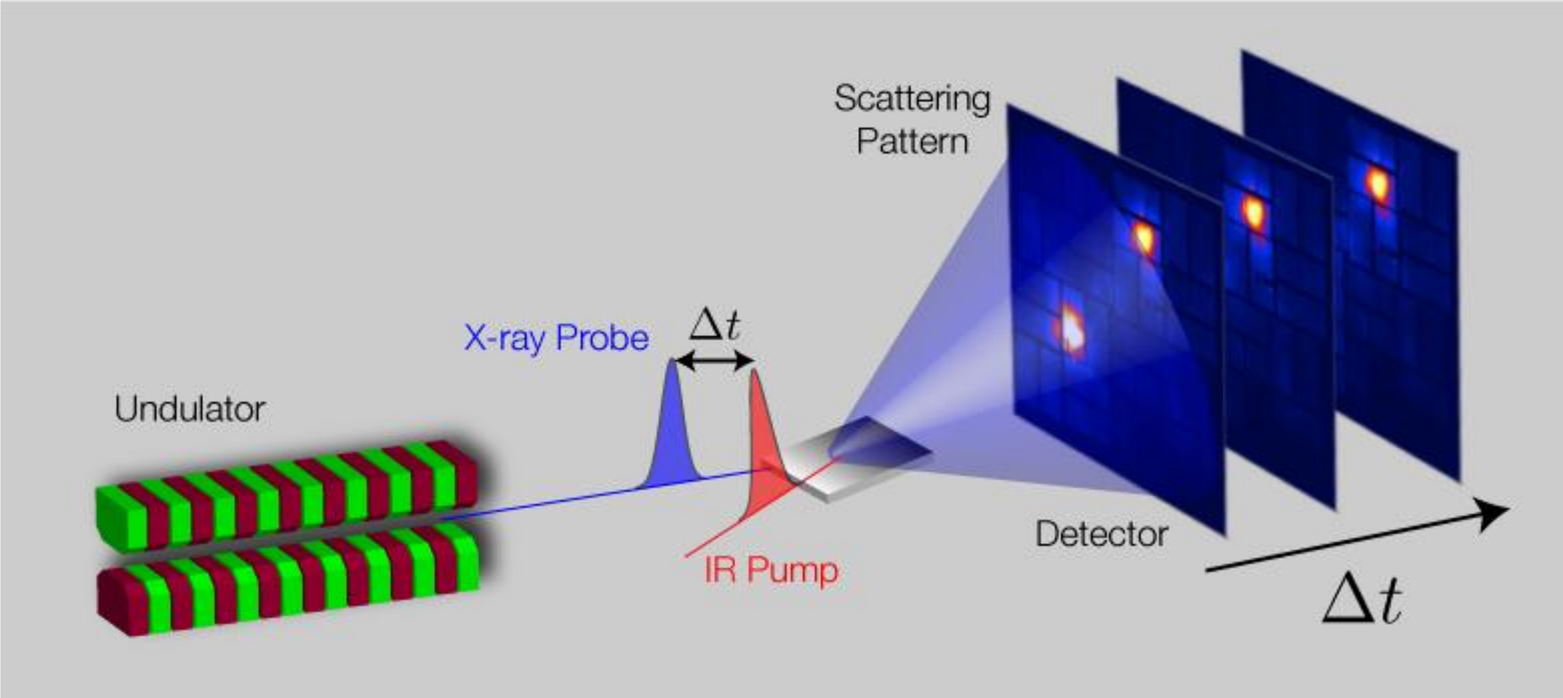


Fig. I.i1. History of the peak brilliance (in photons/s/mrad^2/mm^2/0.1% bw) of X-ray sources.

⇒ ***X-ray FEL provide instantaneous photon flux for femto-second flash pictures of nanometer objects***

http://www.psi.ch/swissfel/CurrentSwissFELPublicationsEN/SwissFEL_Science_Case_small.pdf

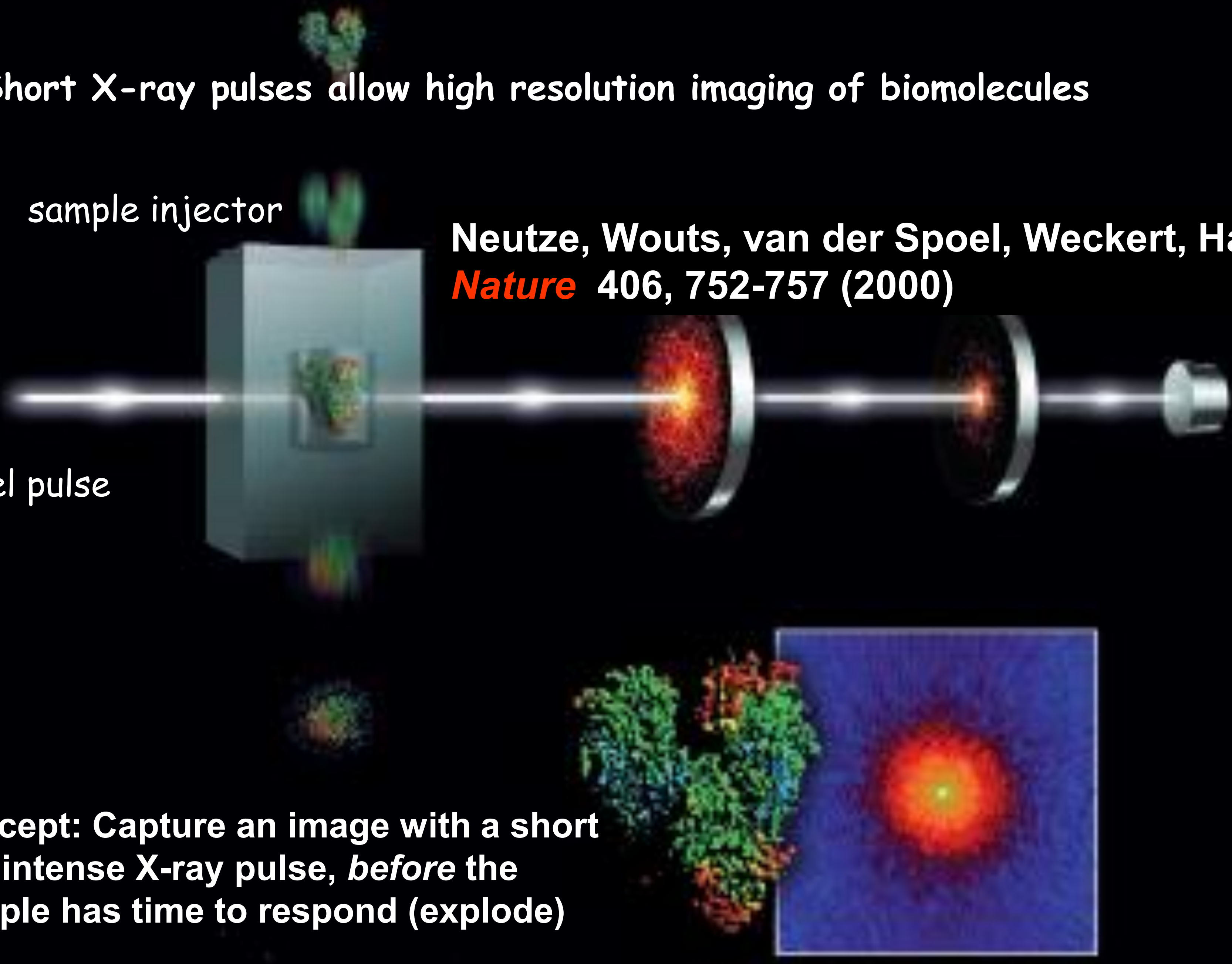
Ultrafast dynamics pump-probe experiments



Picture from http://unlcms.unl.edu/physics-astronomy/fuchs-group/ultrafast-x-ray-diffraction

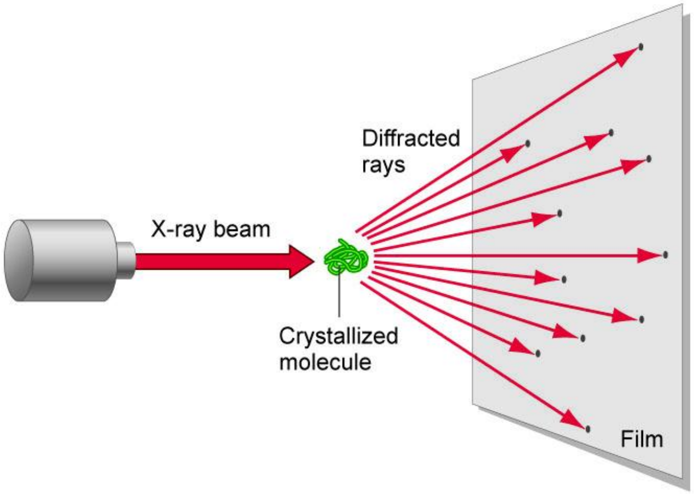
Short X-ray pulses allow high resolution imaging of biomolecules

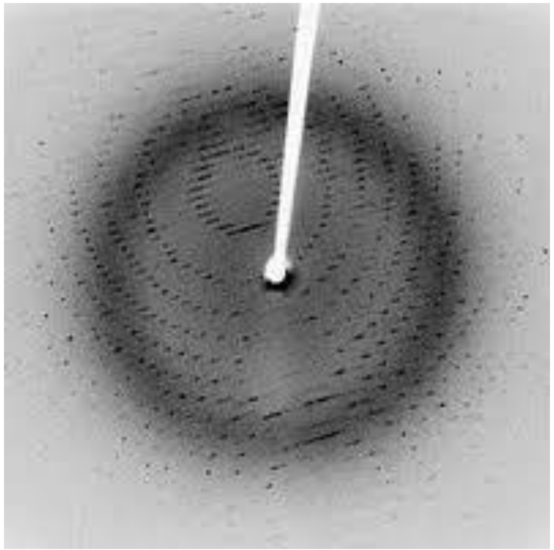
Neutze, Wouts, van der Spoel, Weckert, Hajdu
Nature 406, 752-757 (2000)



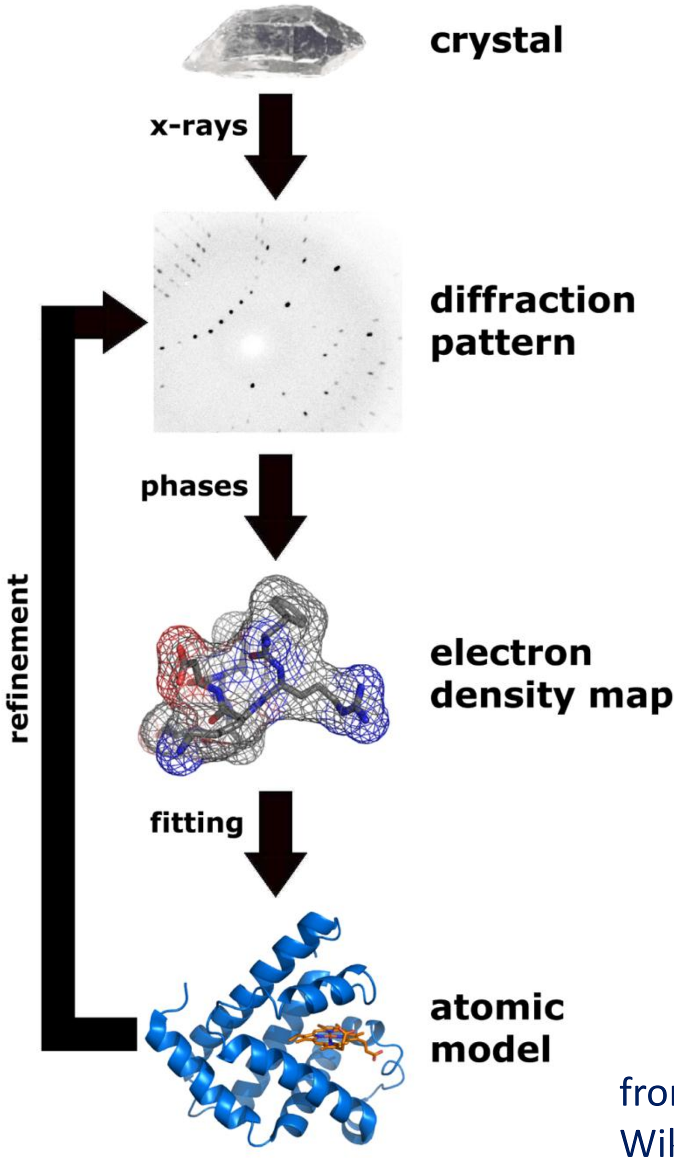
Concept: Capture an image with a short and intense X-ray pulse, *before* the sample has time to respond (explode)

Reconstruct nano object from diffraction image



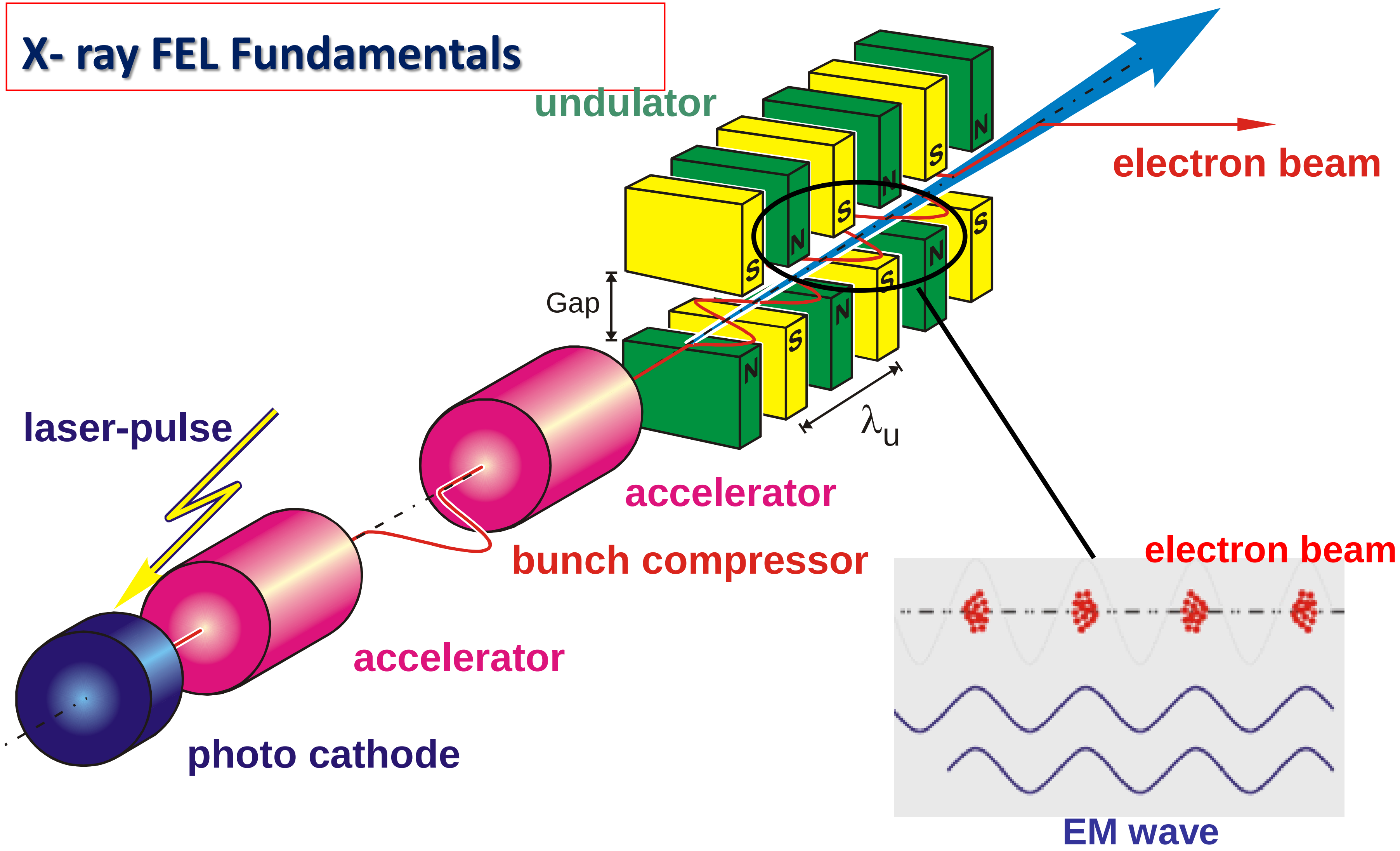


diffraction image

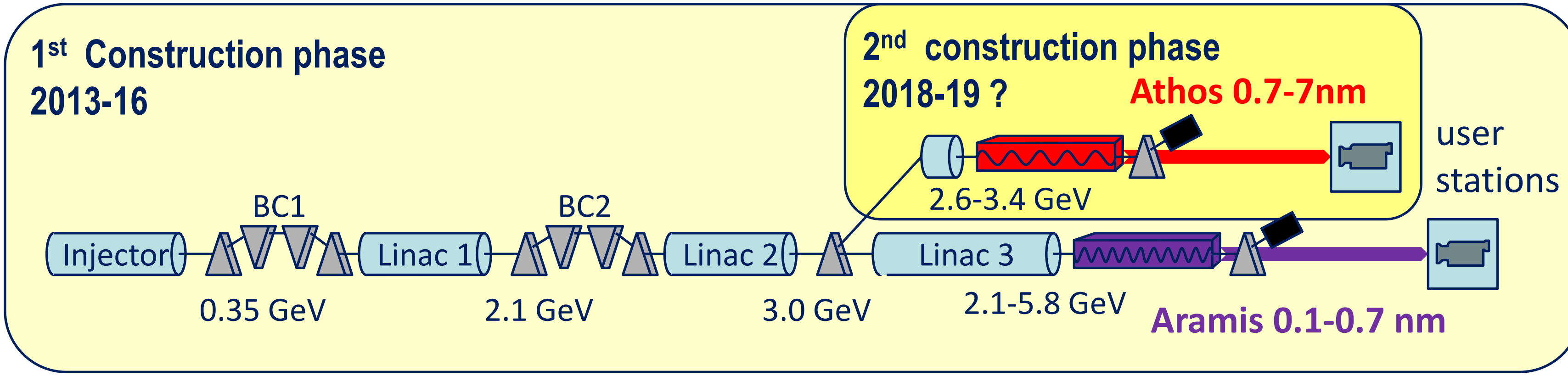


from
Wikipedia

X- ray FEL Fundamentals



SwissFEL in a nutshell



Aramis

Hard X-ray FEL, λ=0.1-0.7 nm
Linear polarization, variable gap, in-vacuum Undulators
First users 2017
Operation modes: SASE & self seeded

Athos

Soft X-ray FEL, λ=0.7-7.0 nm
Variable polarization, Apple II undulators
First users 2019 ?
Operation modes: SASE & self seeded

Main parameters

Wavelength from	1 Å - 70 Å
Photon energy	0.2-12 keV
Pulse duration	1 fs - 20 fs
e^- Energy	5.8 GeV
e^- Bunch charge	10-200 pC
Repetition rate	100 Hz

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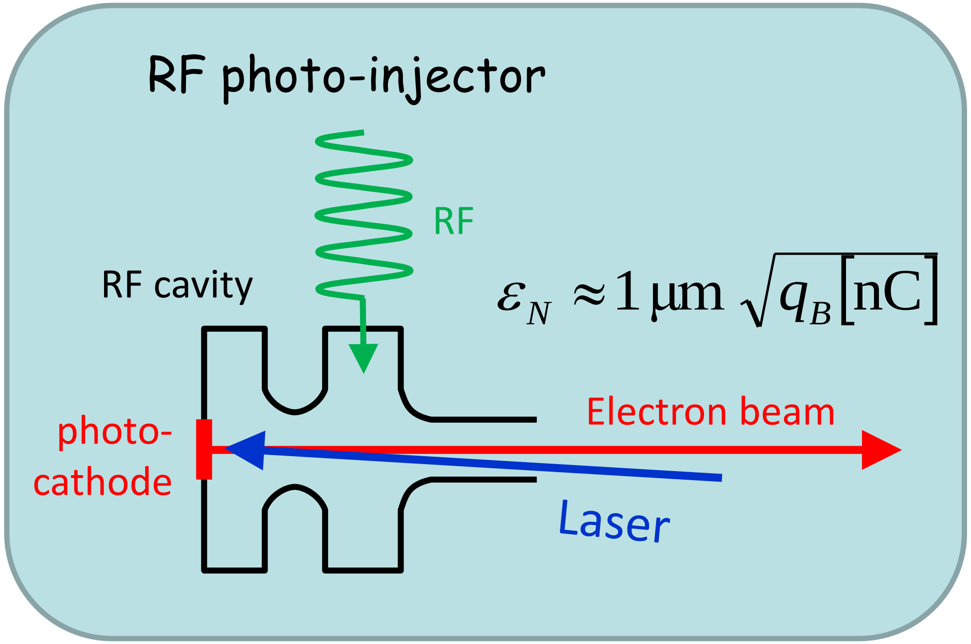
Injector

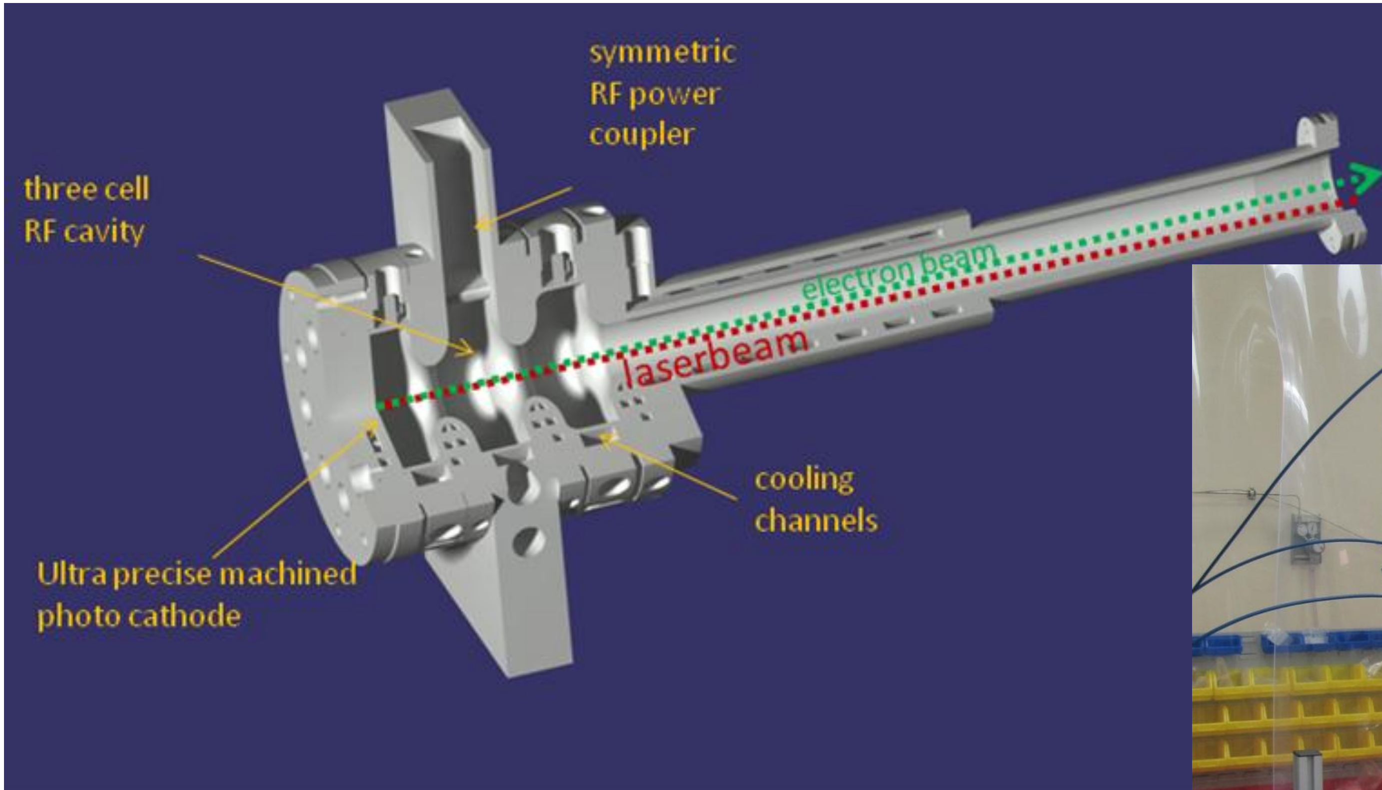
FEL requires $$\varepsilon_N \approx 5\gamma \frac{\lambda}{4\pi}$$

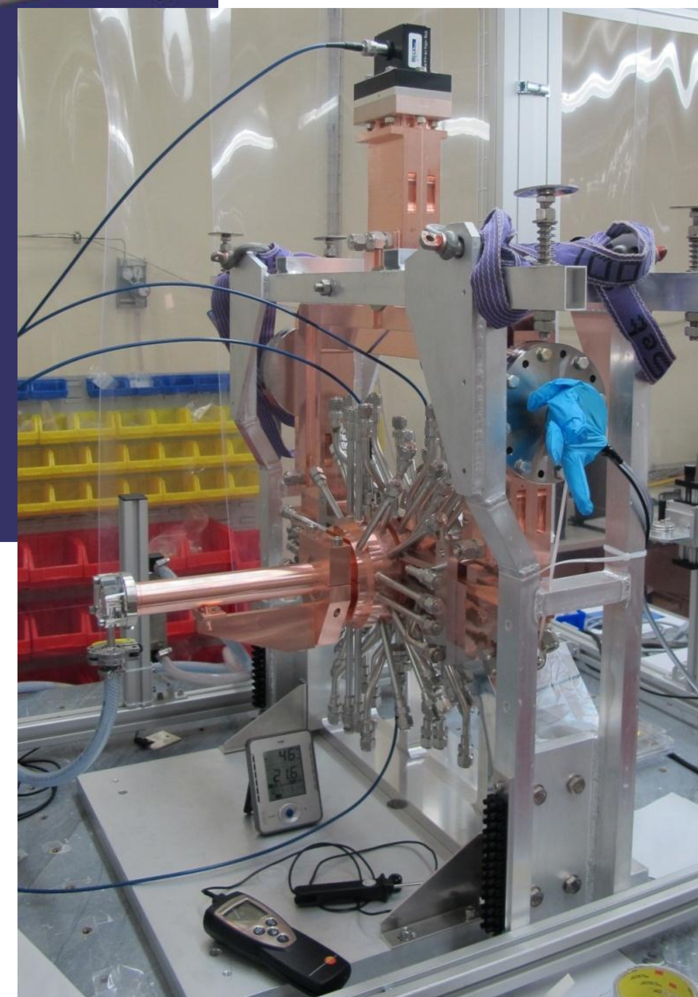


$$\varepsilon_N \approx 1\,\mu\text{m}\,\sqrt{q_B[\text{nC}]}$$

$\lambda = 1$ Å $\Rightarrow$ $\varepsilon_N \leq 0.4$ µm $\Rightarrow$ $q_B \leq 0.2$ nC

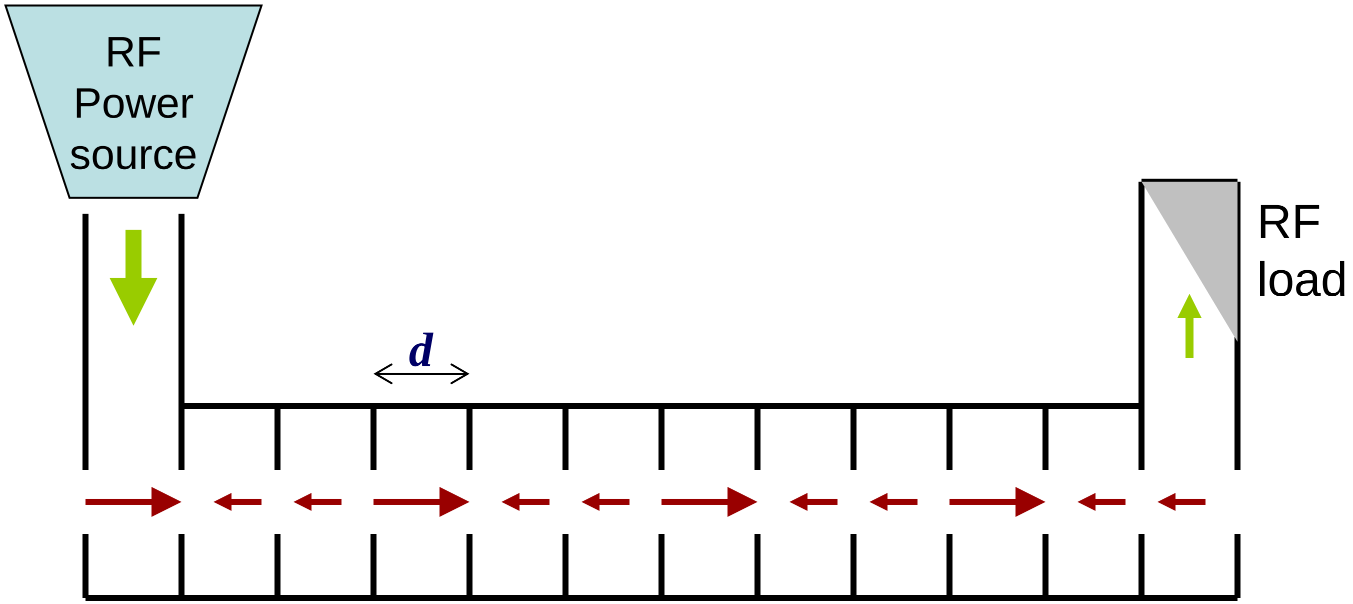
New SwissFEL RF gun





Beam energy	7 MeV
Cathode field	100 MV/m
Repetition rate	100^Hz
RF frequency	2.998 GHz

Linear accelerator

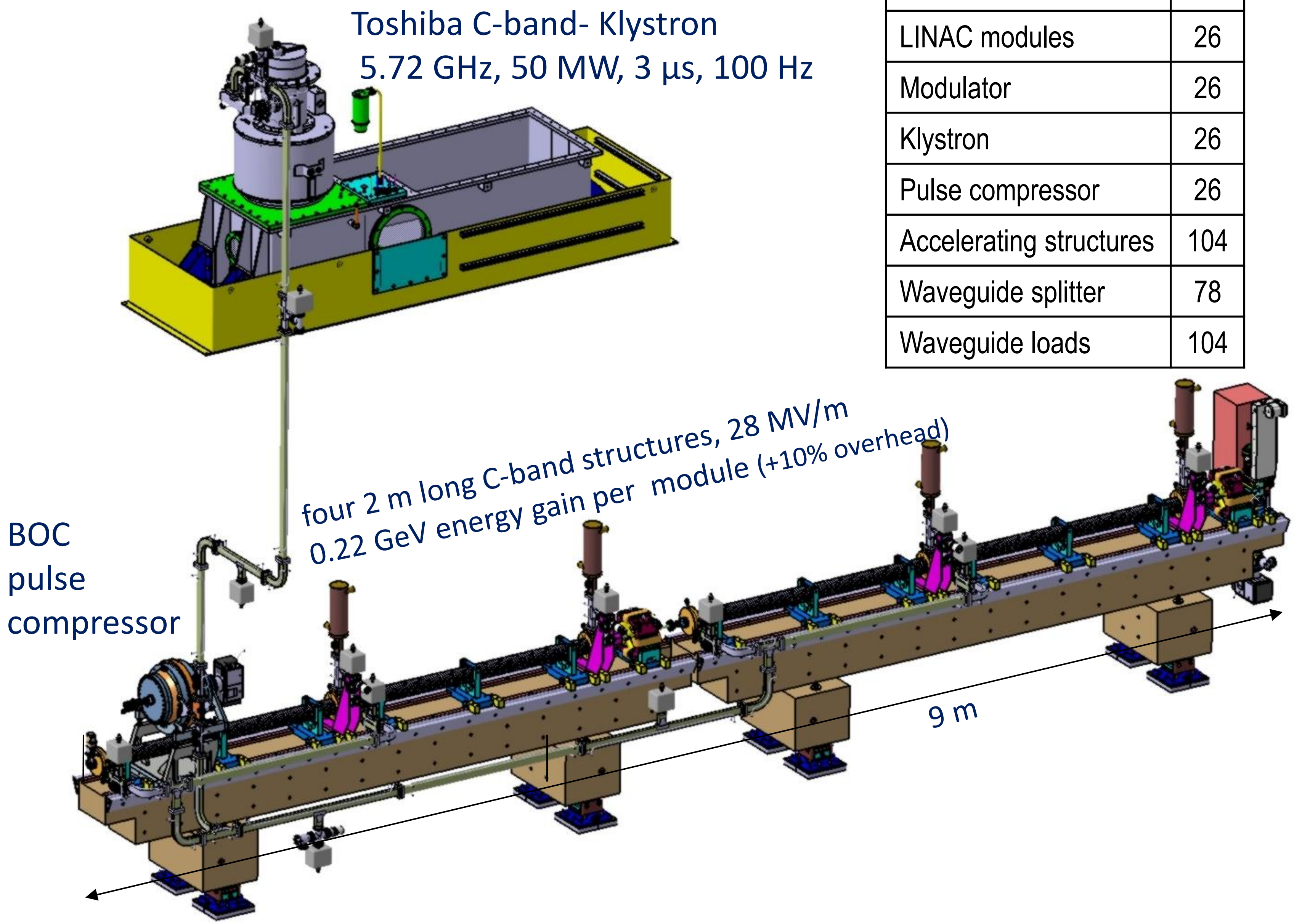


Electrically coupled TM_{010} resonant cavities

Condition for acceleration $\Delta\varphi = \omega/c \cdot d$
With $\Delta\varphi$ the phase difference between adjacent cells

SwissFEL Main Linac building block

Main LINAC	#
LINAC modules	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structures	104
Waveguide splitter	78
Waveguide loads	104



Comparison power consumption for RF plants

Beam energy

SwissFEL	5.8 GeV
SACLA	8.0 GeV
LCLS	13.6 GeV

small emittance
short period undulators

Accelerating field

SwissFEL	28 MV/m
SACLA	35 MV/m
LCLS	17 MV/m

compromise between power consumption and facility length

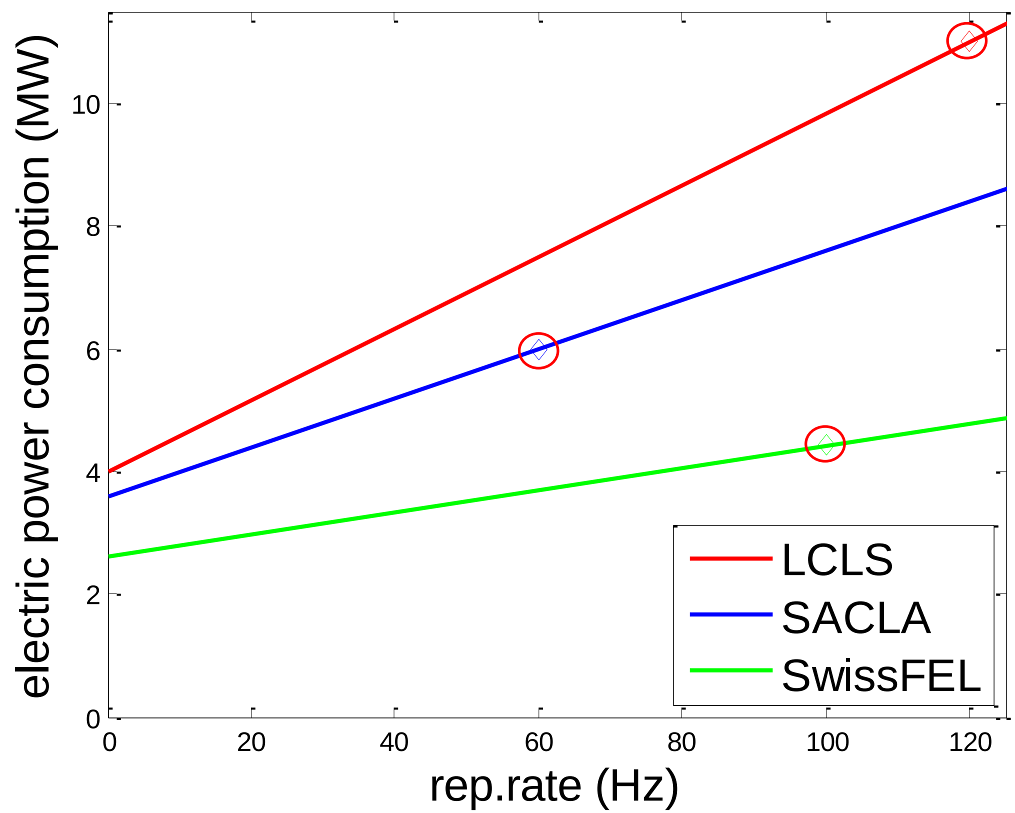
$$P_{HF} = \frac{V \cdot E}{R'}$$

Effective* Impedance

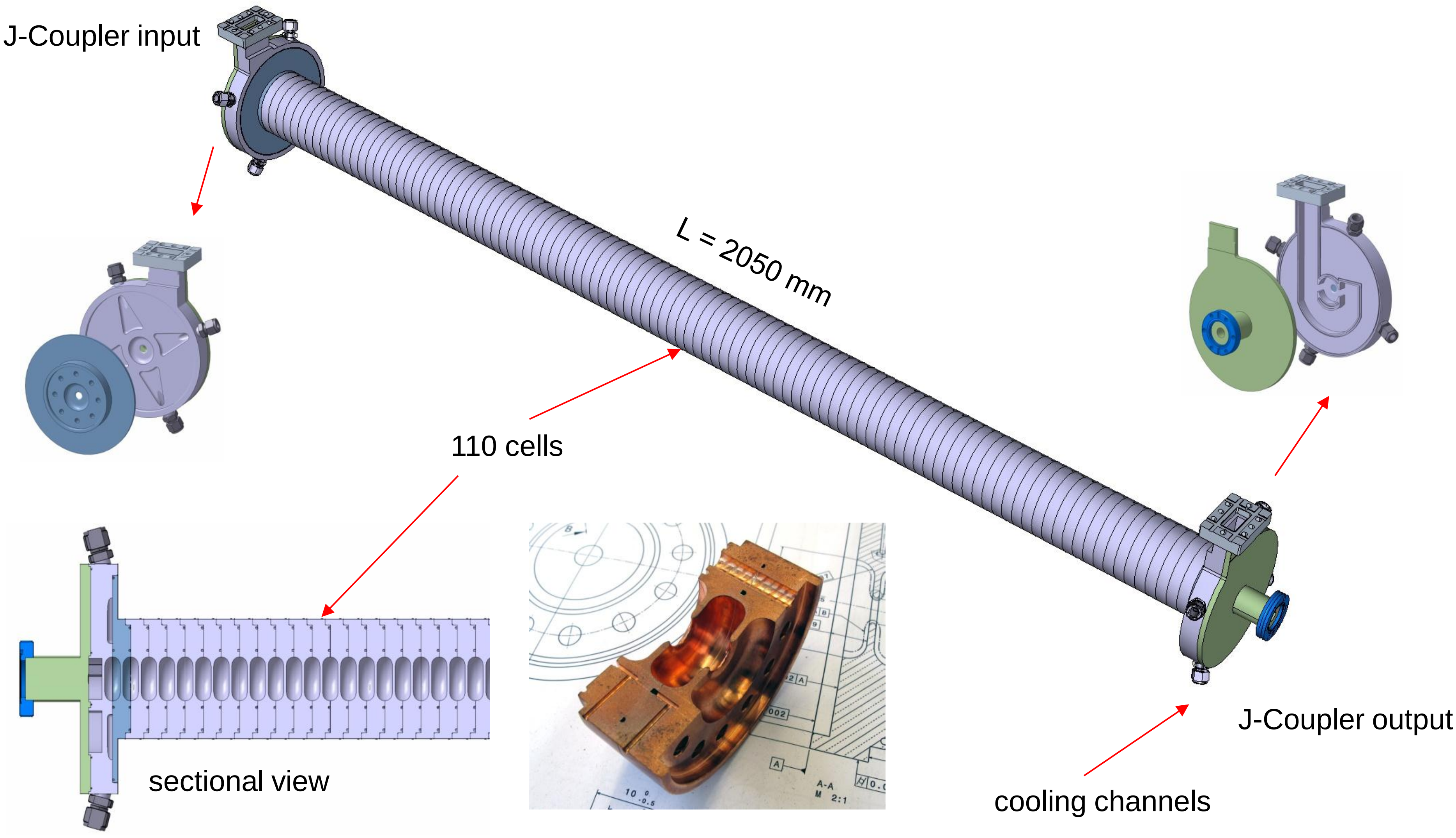
SwissFEL	168 MΩ/m
SACLA	125 MΩ/m
LCLS	80 MΩ/m

C band frequency
structure geometry
pulse compression

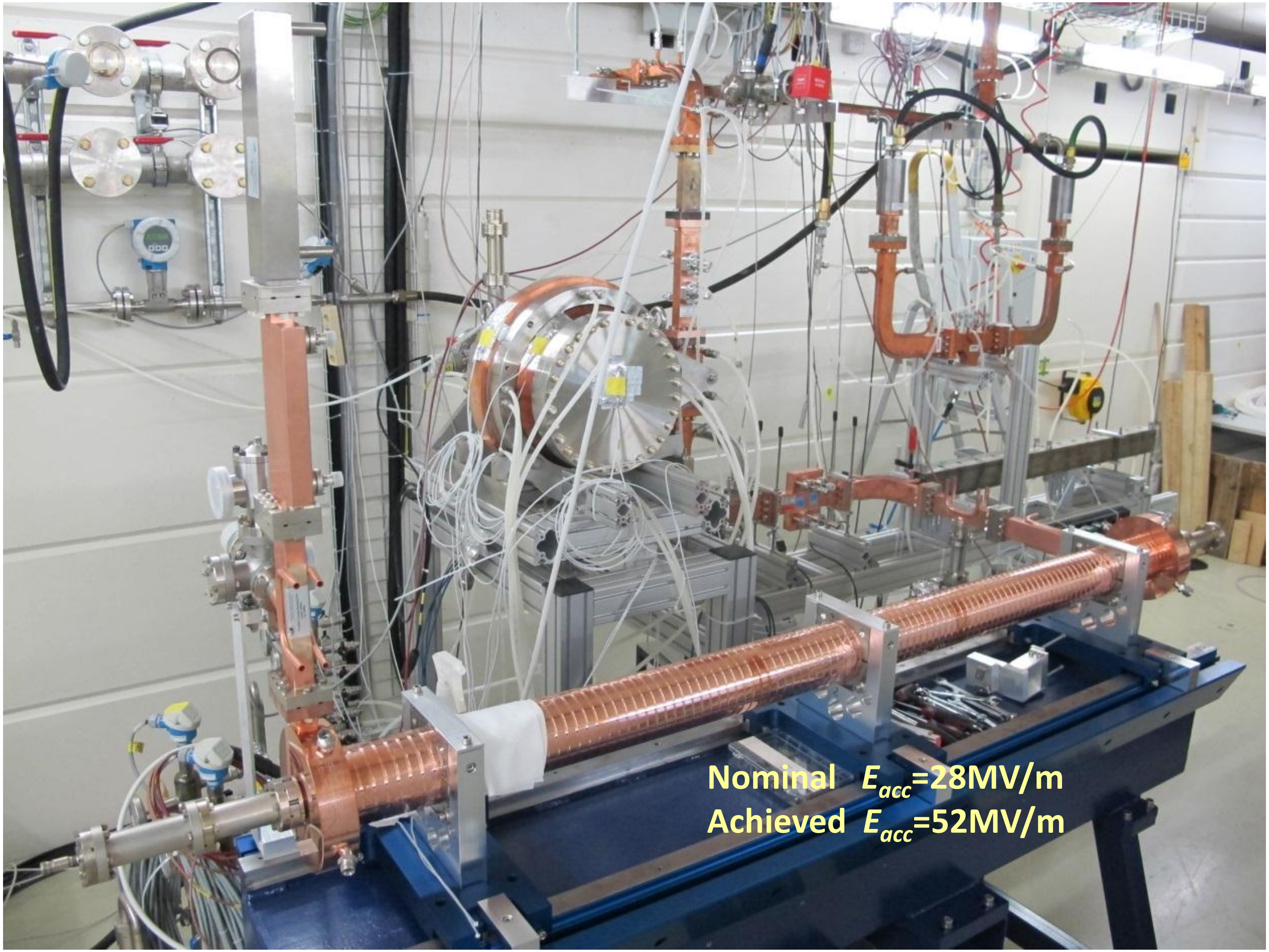
*not classical shunt impedance
but with correction for pulse compression
(Klystron power to effective energy gain)



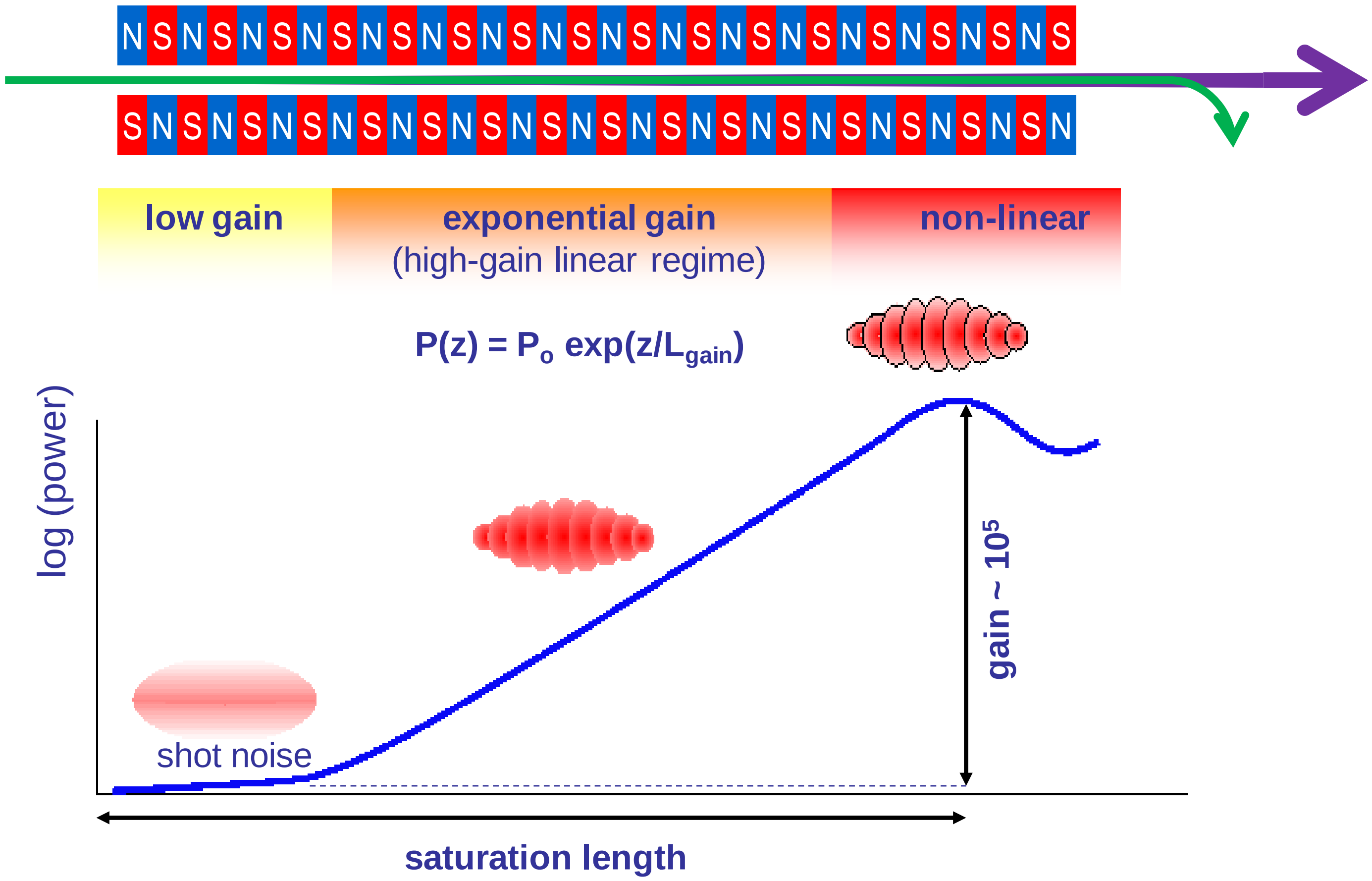
SwissFEL C-band accelerating structure



C-band structure with BOC pulse compression in RF power test area



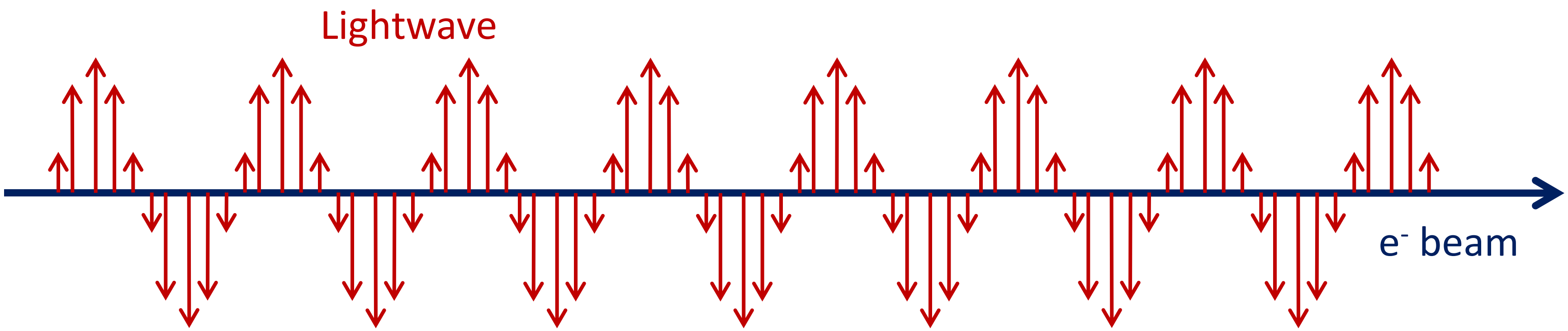
SASE principle



FEL amplifier without mirrors and without input signal ⇒ applicable for large wavelength range

FEL's, short introduction I

Electron beam with straight trajectory overlaid with Lightwave

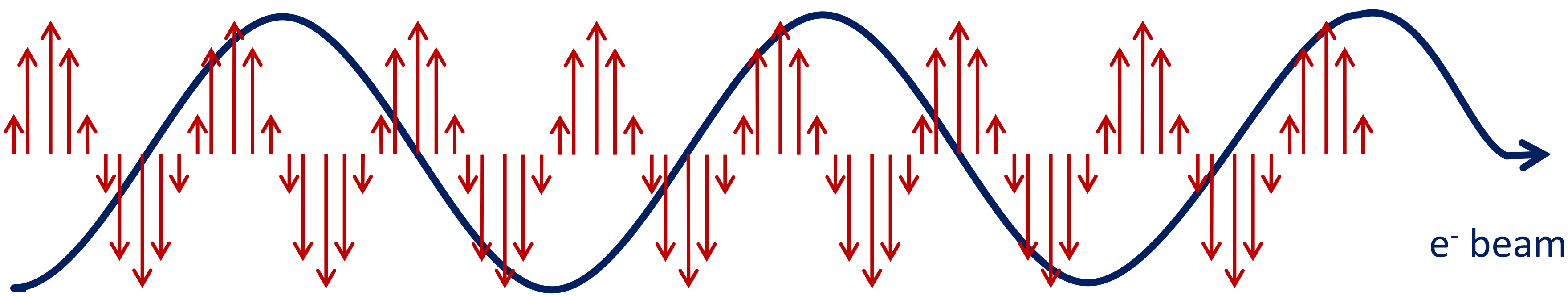


Energy exchange lightwave - electron $\frac{dW}{dt} = \vec{\nabla} W \frac{d\vec{x}}{dt} = e\vec{E} \cdot \vec{v} = 0$

$\Rightarrow$ no energy can be transferred between electrons and light wave

FEL's, short introduction II

Electron beam with wiggling trajectory in undulator overlaid with Lightwave

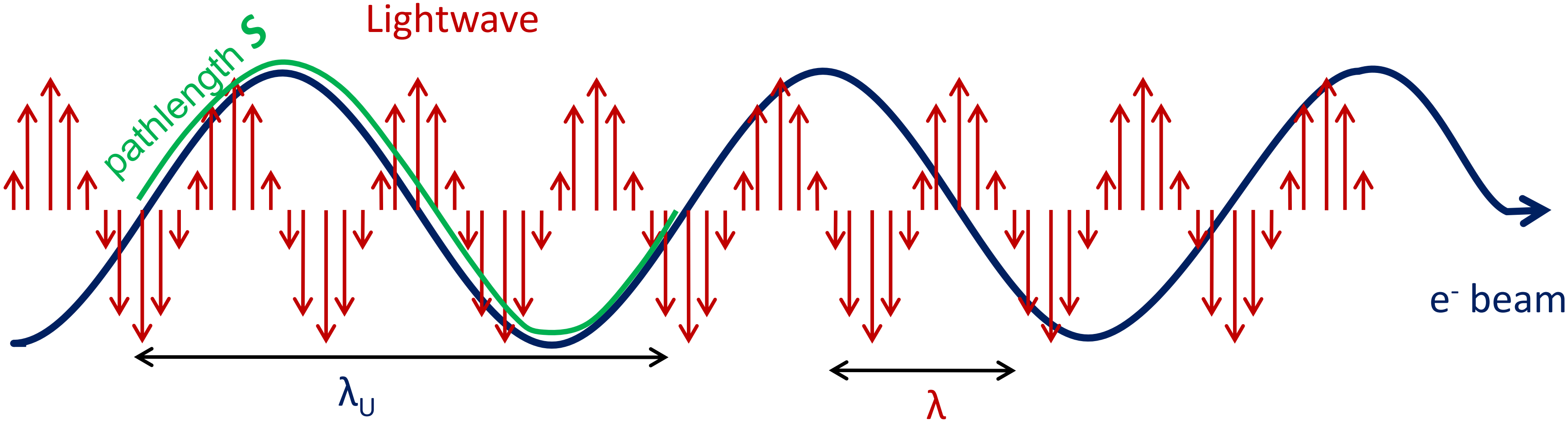


$$\text{Energy exchange lightwave - electron } \frac{dW}{dt} = e\vec{E}\cdot\vec{v} \neq 0 \text{ because } \vec{v}_{\perp} \neq 0$$

$\Rightarrow$ Energy can be transferred between electrons and light wave

FEL's, short introduction III

Resonant energy transfer



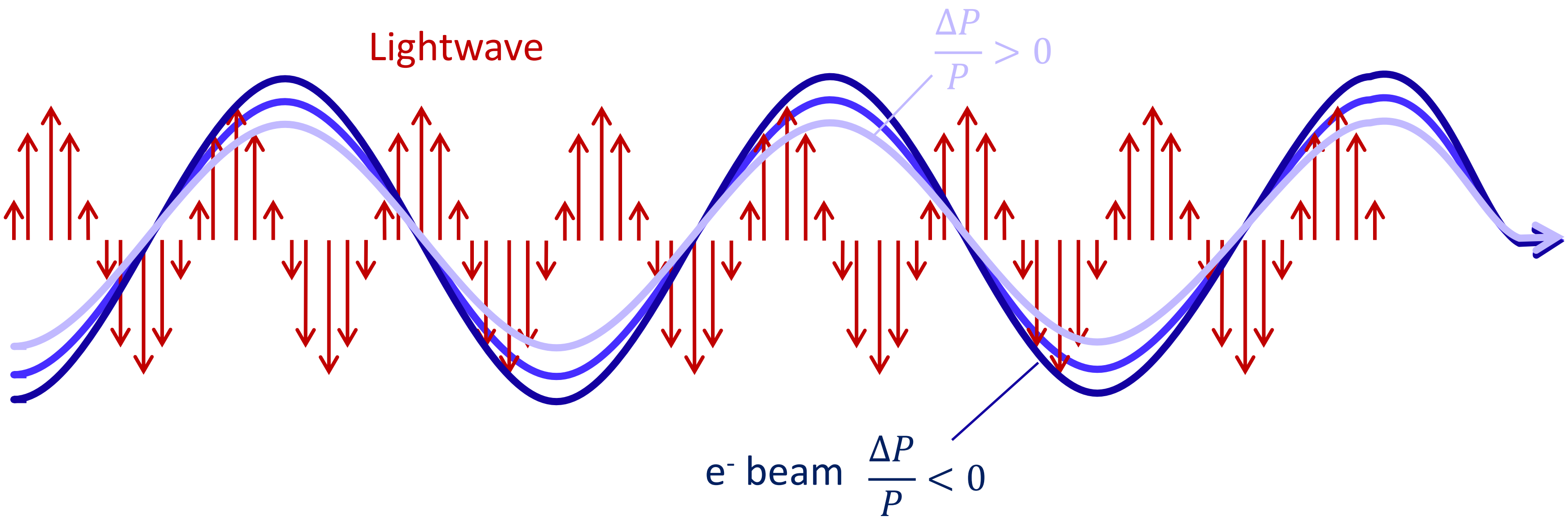
Resonance condition :

$$T_e = T_L + \frac{n\lambda}{c} \quad \Rightarrow \quad \frac{\mathrm{S}}{\beta \mathrm{c}} = \frac{\lambda_U}{c} + \frac{n\lambda}{c} \quad \Rightarrow \quad \lambda = \frac{\lambda_U}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$\text{with} \quad K = \frac{e}{2\pi\, m_e c} B_U \lambda_U$$

FEL's, short introduction IV

Electron beam bunching



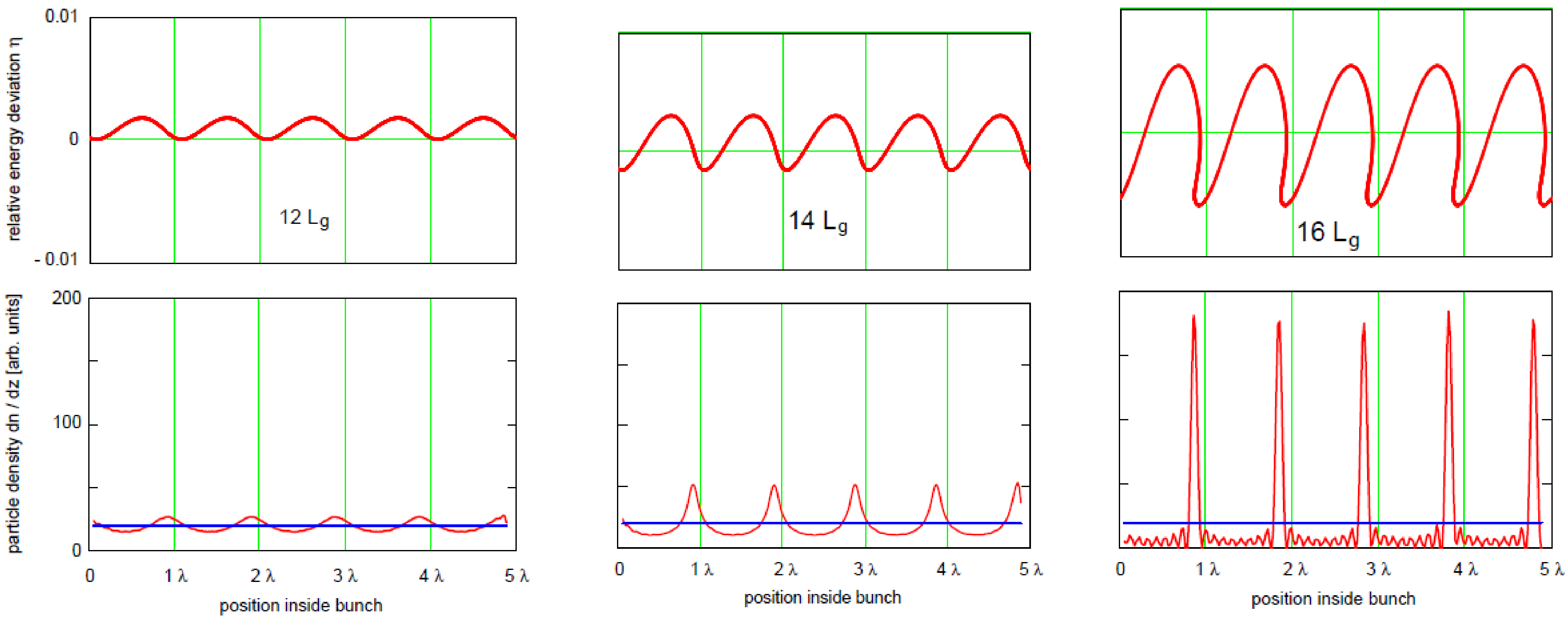
Energy change $\frac{dW}{dt} = e\vec{E} \bullet \vec{v}$ depends on e⁻ timing relative to phase of lightwave.

Different electron energies have different pathlength

$\Rightarrow$ Electrons get bunched with light period λ

FEL's, short introduction V

Electron beam micro bunching for three positions along undulator



e^- micro bunches exchange coherently energy with lightwave

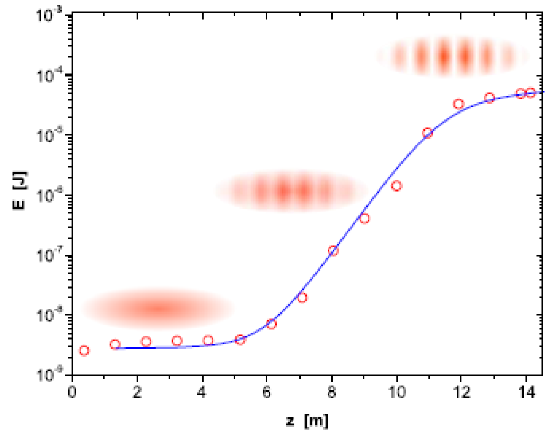
$\Rightarrow$ Amplification of Lightwave

FEL's, short introduction VI

At very short wavelength two problems for FEL

1. Neither high reflectivity mirrors for oscillator configuration nor seeding source of coherent light for amplifier available

   $\Rightarrow$ SASE operation,
   shot noise of e^- beam is amplified
   in single pass FEL.
   Since initial noise signal is small
   many gain length i.e. long undulators



2. Efficient lasing requires good overlap between electron and light beam

Light beam	$w^2(s) = w_0^2 + \frac{\lambda^2}{\pi^2 w_0^2} s^2$	$\Rightarrow \quad \varepsilon \leq \frac{\lambda}{4\pi}, \qquad \varepsilon = \frac{\varepsilon_N}{\gamma}$
Electron beam	$\sigma^2(s) = \sigma_0^2 + \frac{\varepsilon^2}{\sigma_0^2} s^2$	

Either a very brilliant electron source with very small ε_N
or very high electron energy γ are required !

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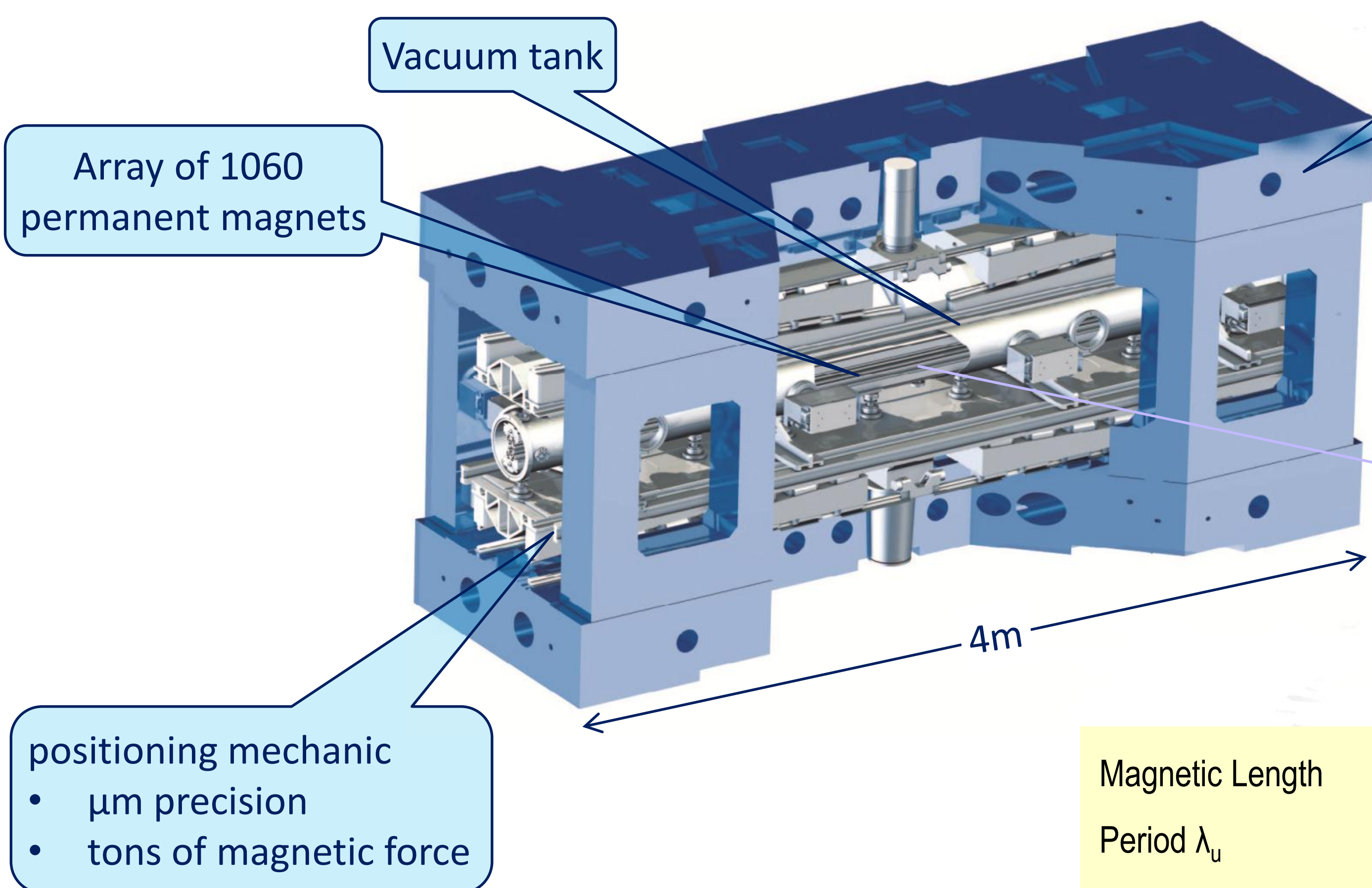
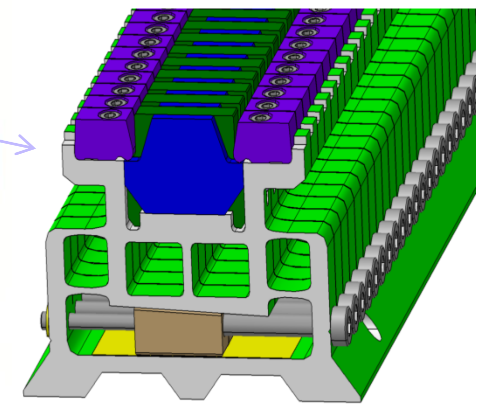
U15 Undulator for ARAMIS beamline

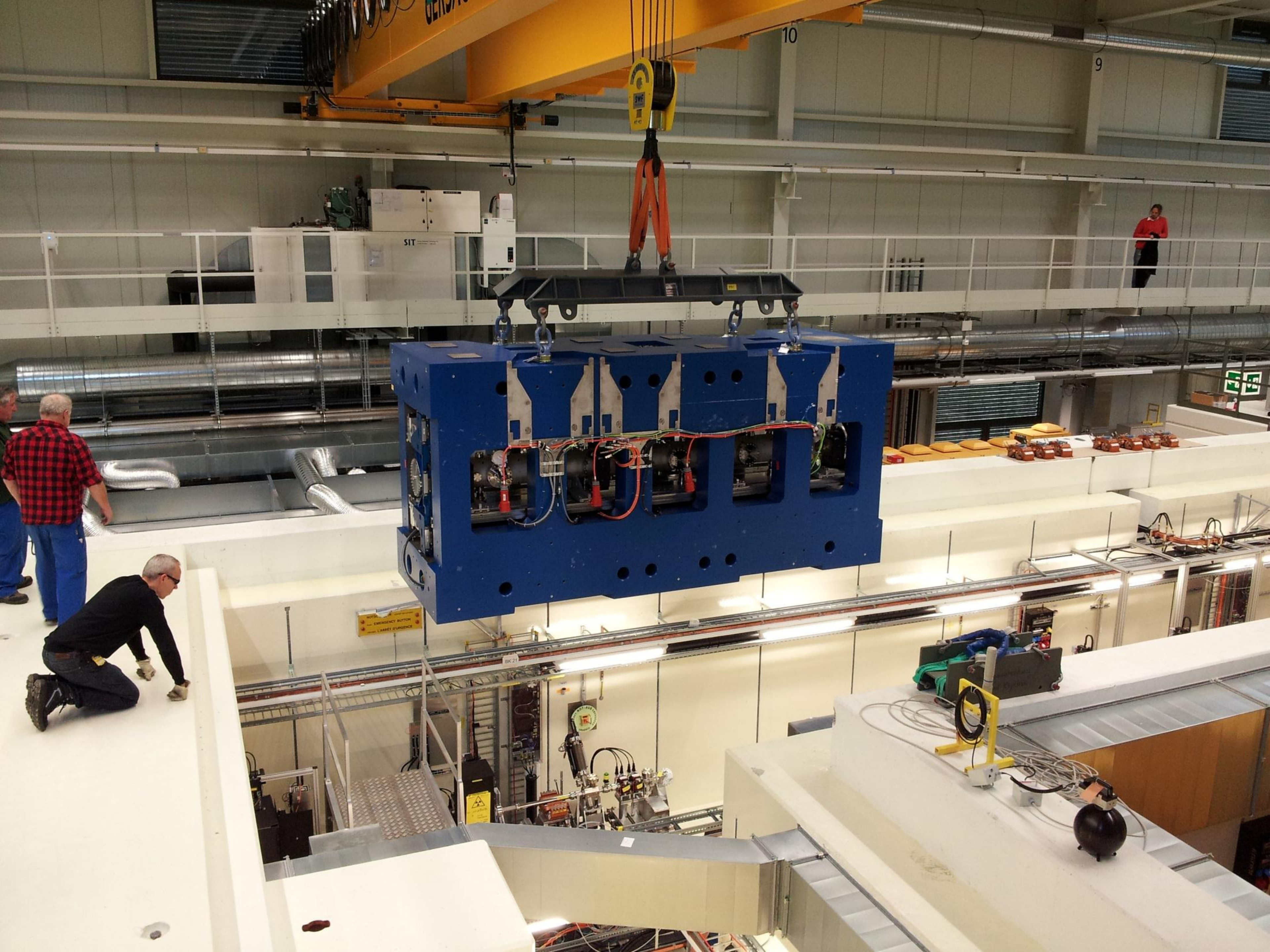




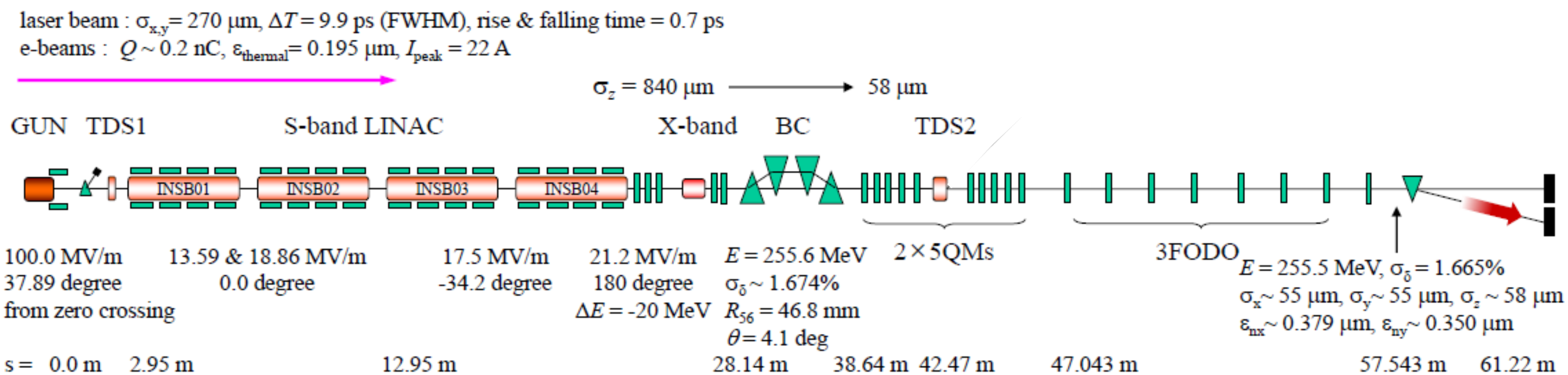
Magnetic Length	3990 mm
Period λ_u	15 mm
Gap	3.2 4.2 4.7 5.5 mm
Undulator K value	1.8 1.4 1.2 1.0
Magnetic Field Bz on axis	1.3 1.0 0.9 0.7 T
Magnetic Material	NdFeB-Dy
Pole Material	Permendur (CoFeVa)

U15 hybrid, in-vacuum undulator

12 x 17t of precision mechanic

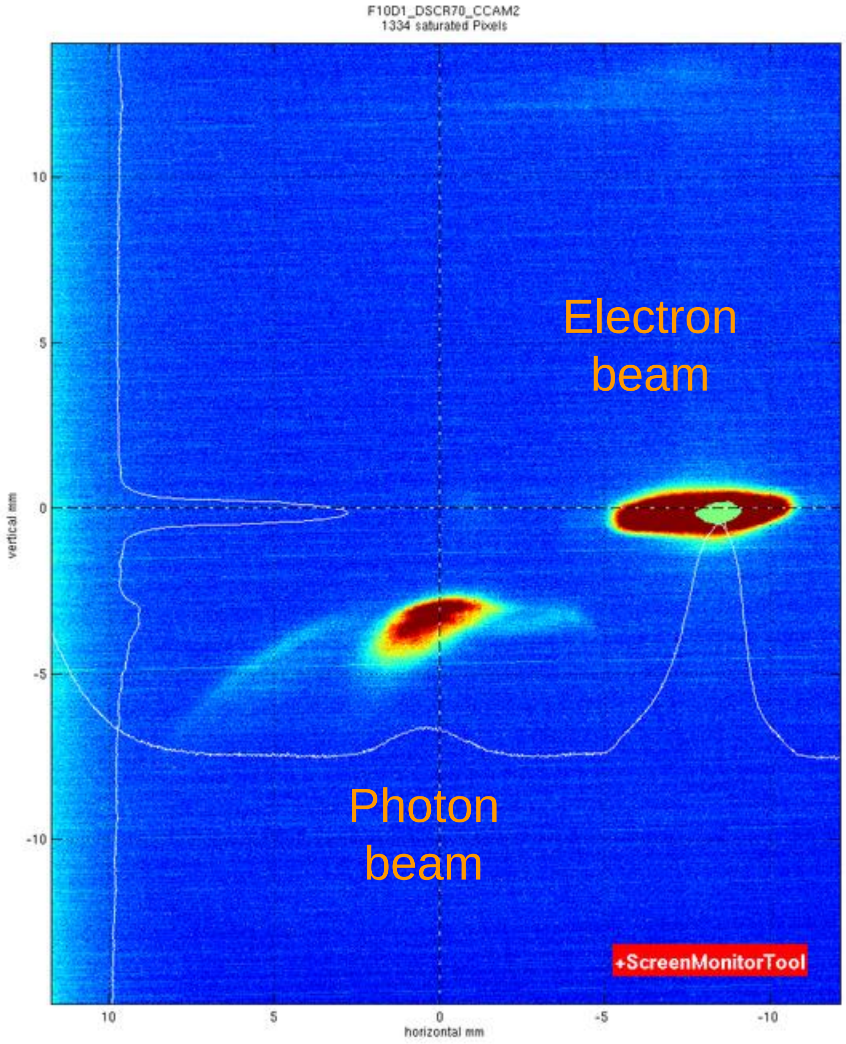

10
9
SIT
EMERGENCY BUTTON

SwissFEL injector Tesf facility



First SASE @ Test facility SwissFEL (15-01-14)

- Electron parameters: E=220MeV, Q=200pC
- Radiation wavelength derived from undulator parameters and electron energy:
  λ=~45-90nm (very first lasing @ 80nm)
- This is the first FEL light produced in Switzerland



Magnet Power Supplies for SwissFEL

List of magnet power supplies

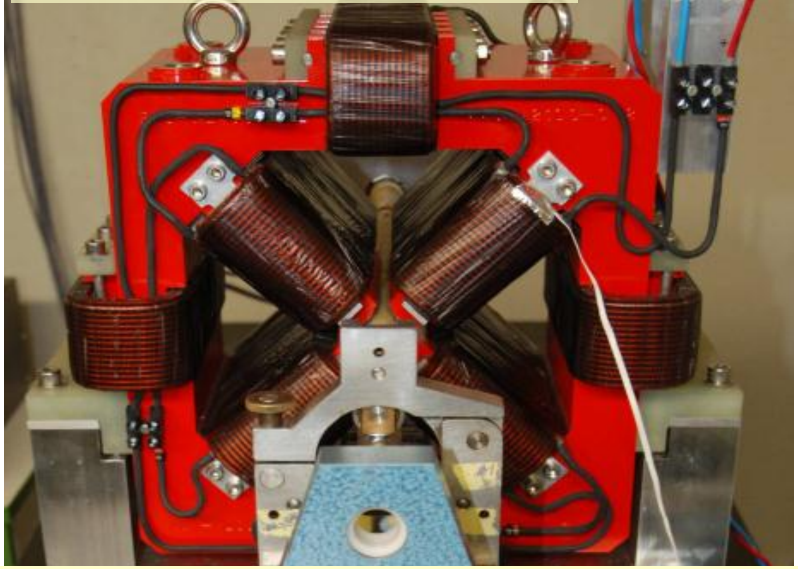
- 556 x 10A
- 13 x 20A
- 19 x 50A
- 16 x 150A

Typical magnet resistance are few 100 mΩ

Typical ripple requirements <20-100 ppm

Most magnets are air cooled

SwissFEL standard linac "QFD"
Quadrupole with H&V steerer



Aperture :22 mm
Gradient : 20 T/m
Pole Tip field : 220 mT
Max current : 10 A (air cooled)
Yoke length: 0.150 m
H/V Steering dipoles (integrated): 10 A
Steering max field : 30 mT
Size (mm), weight (kg): (326x326x204);80
M270-50 A steel , laminations : 0.5 mm thick

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Power Supplies (PS) for SwissFEL

Prototype Rack for up to 21 10A-PS

front

rear

Prototype Rack for 4 50A PS and 8 10A PS

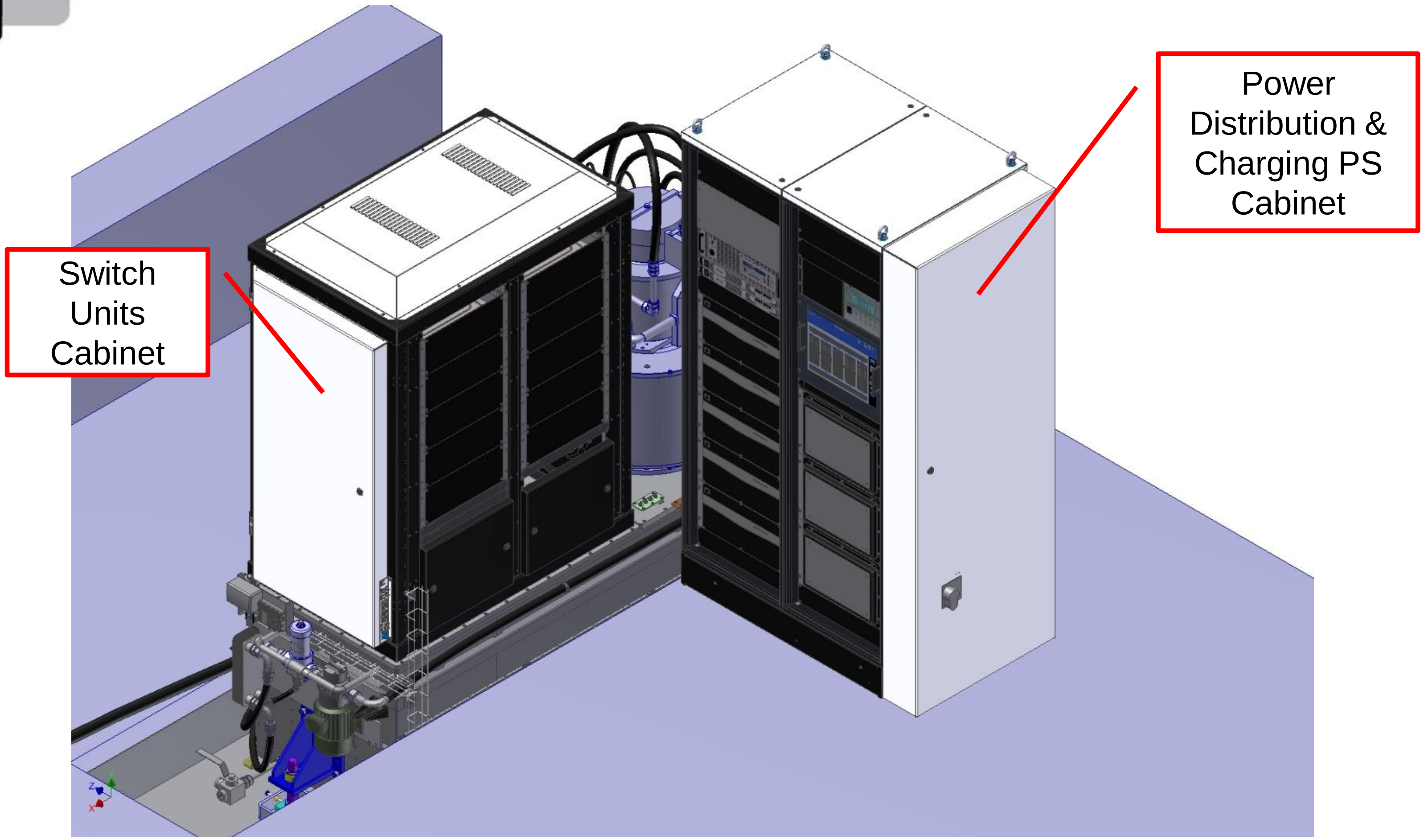
front

rear

courtesy René Künzi

K2-3 FOR C-BAND AT 50 MW-LEVEL, 370kV / 344A / 3µs / 100 Hz

Courtesy of Mikael Lindholm/ Scandinova

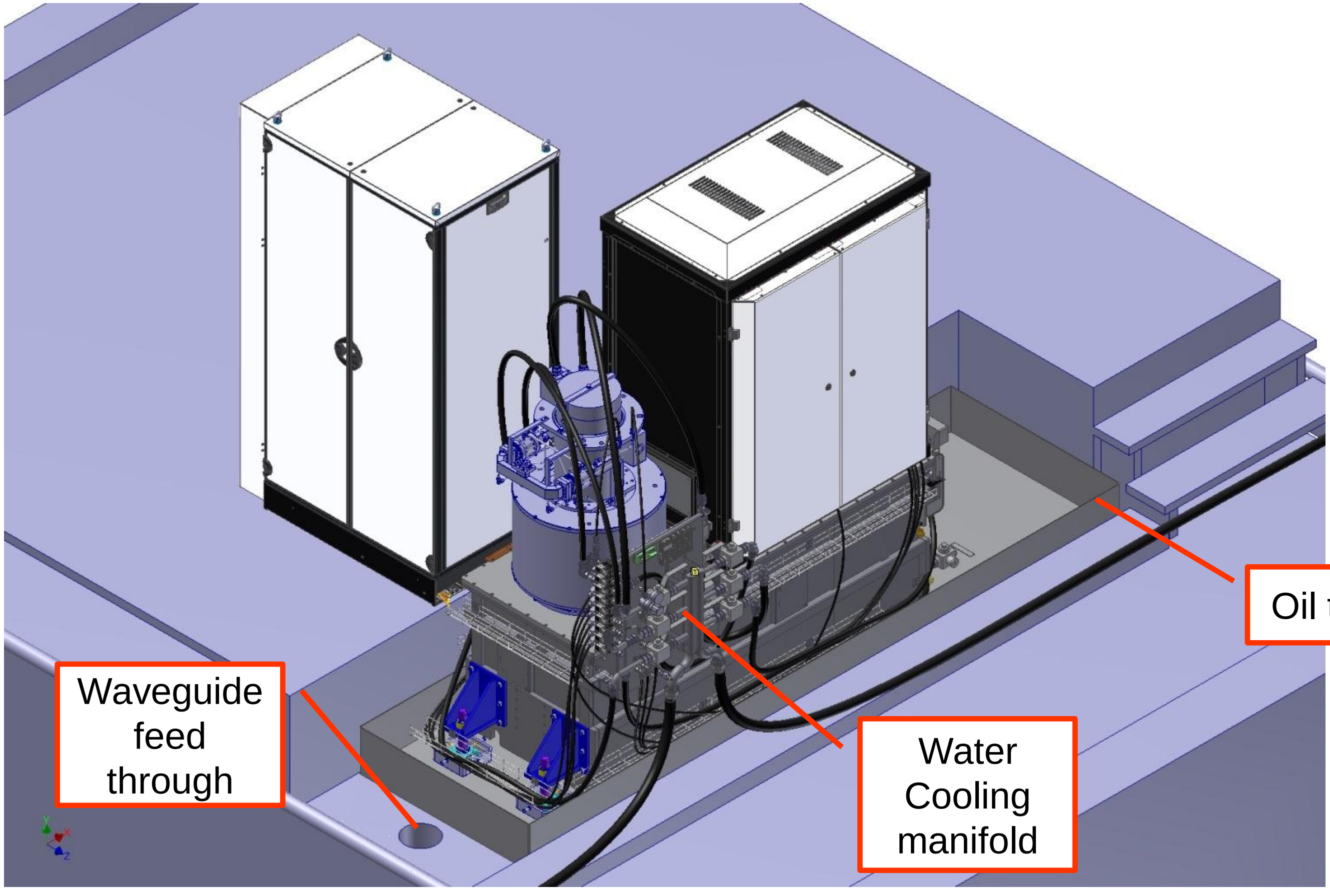


K2 FOR PSI C-BAND PROTOTYPE TEST STAND

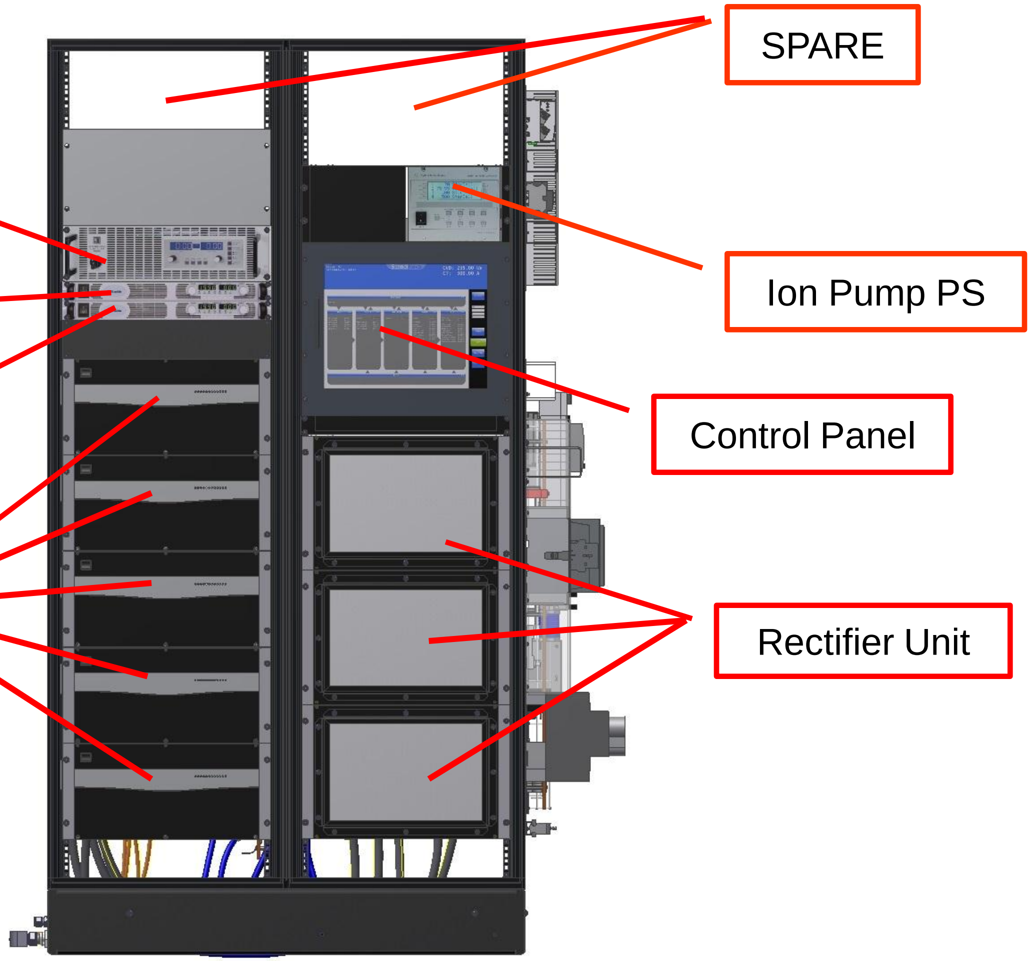
Designed for 20 PPM Stability

K2-3 FOR C-BAND AT 50 MW-LEVEL,

Courtesy of Mikael Lindholm/ Scandinova



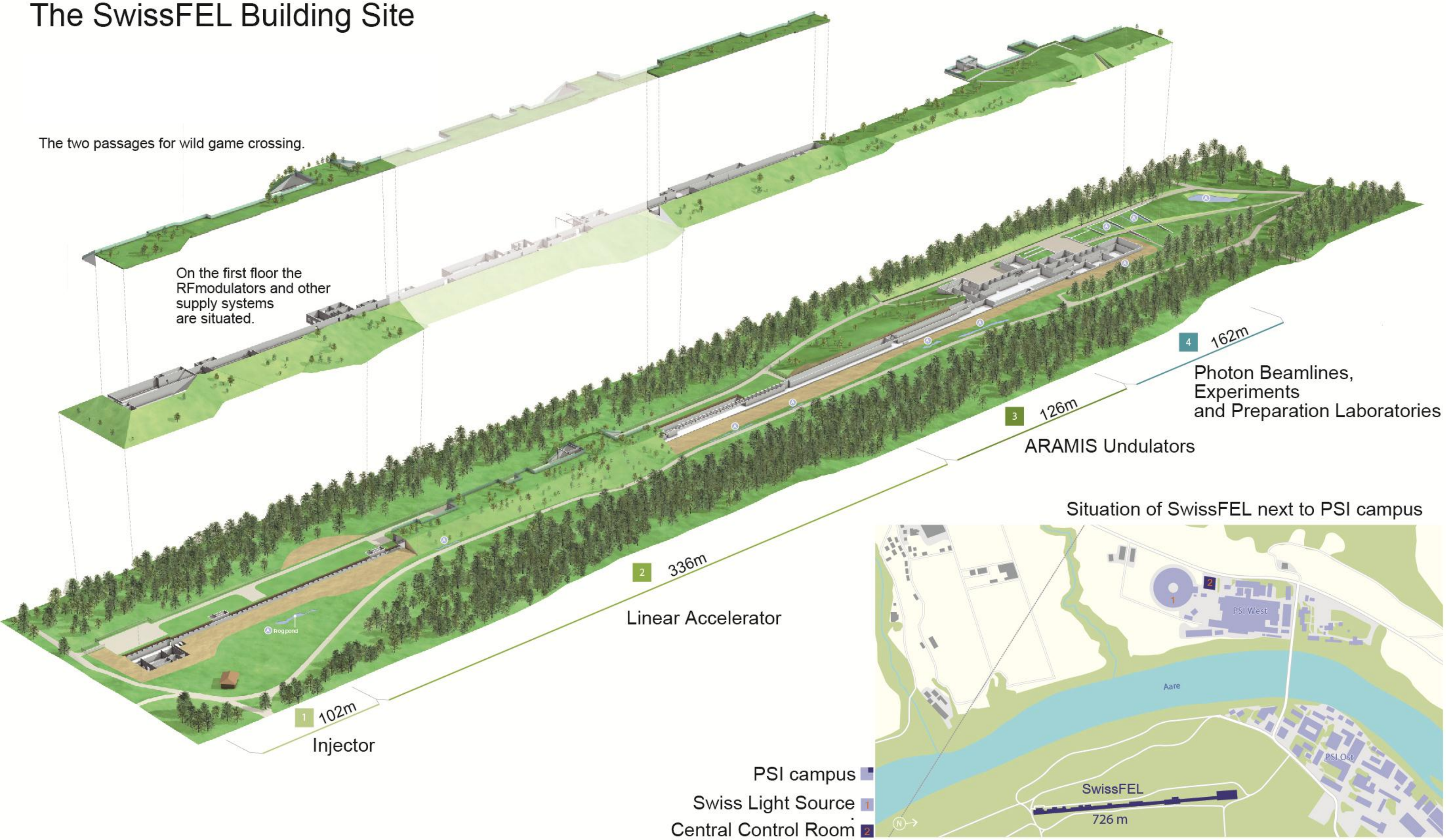
K2-3 FOR C-BAND AT 50 MW-LEVEL



Courtesy of Mikael Lindholm/ Scandinova

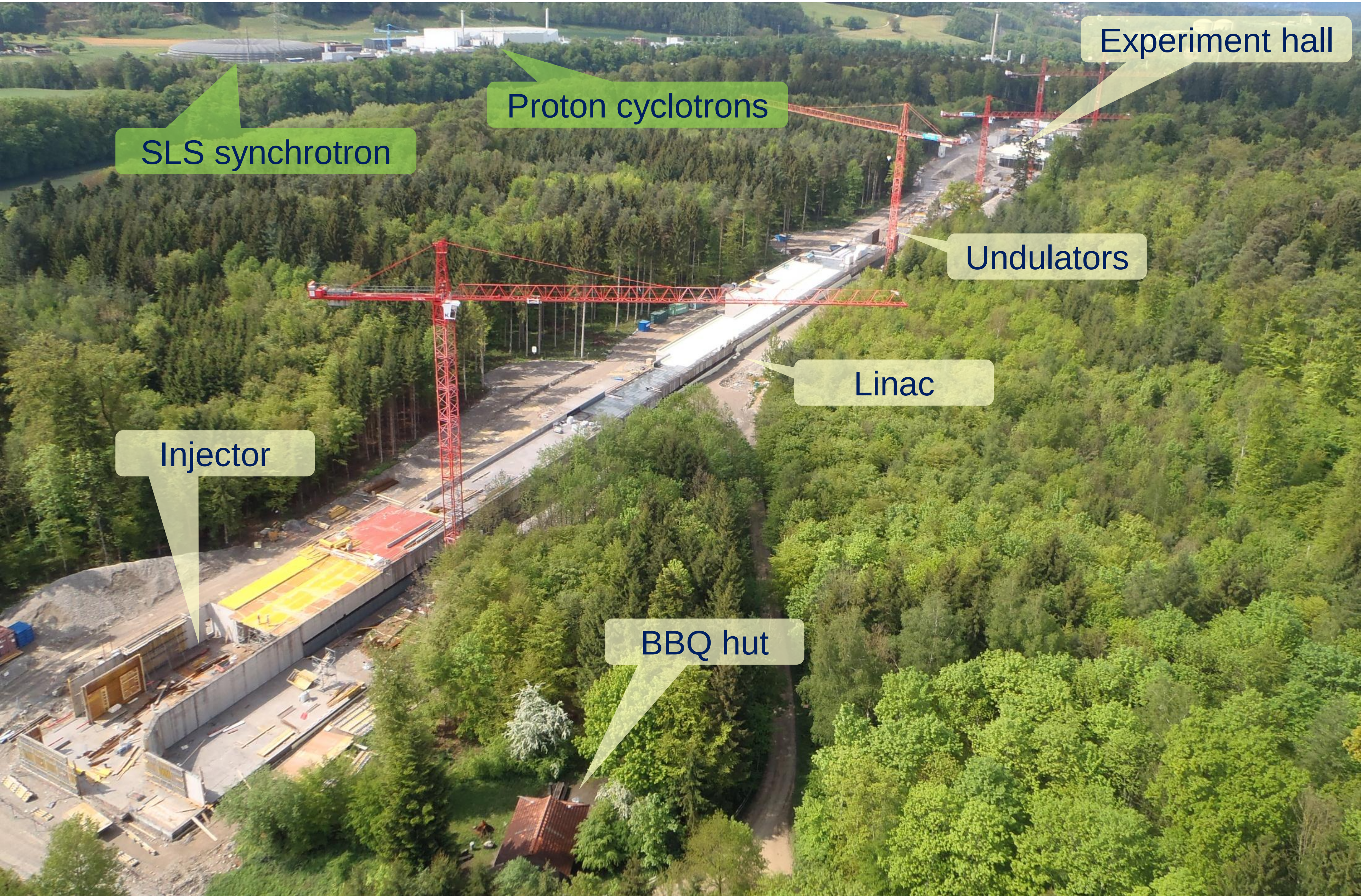
Building

The SwissFEL Building Site



SwissFEL construction site

May 2014



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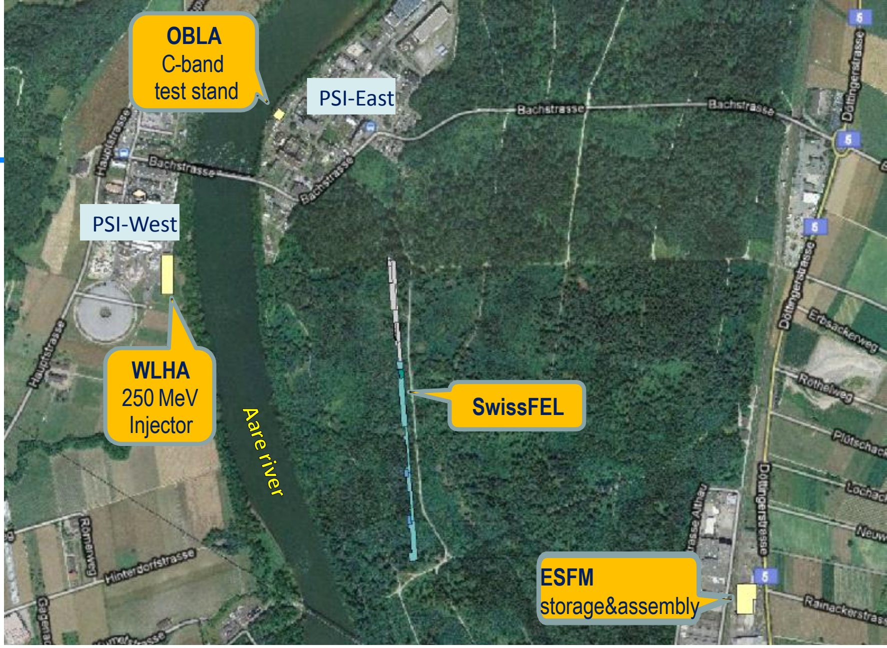
Installation & Commissioning overview



		2014	2015	2016	2017
OSFA	Injector	civil constr. & infrastruct.	Injector installation	Inj. Com. / Commissioning	Commissioning / Pilot experiments
	Undulator-lab	civil constr. & infrastruct.	Undulator assembly & measurement	Undulator assembly & measurement	Pilot experiments
	RF gallery	civil construction & infrastructure	klystron modulators 1-13	klystron modulators 14-26	Pilot experiments
	Linac & FEL tunnel	civil construction & infrastructure	accelerator & FEL	Commissioning	Pilot experiments
	Photon beamlines	civil construction & infrastructure	Photon-beamline	Photon-beamline / Commissioning	Commissioning / Pilot experiments
	Experiments	civil construction & infrastructure		ESA &ESB installation / Commissioning	Commissioning / Pilot experiments
WLHA		Injector beam tests / dismantling	Component pre-assembly and storage	Component pre-assembly and storage	Component pre-assembly and storage
ESFM		Component pre-assembly and storage	Component pre-assembly and storage	Component pre-assembly and storage	
OBLA		C-band component powertests	C-band component powertests	C-band component powertests	C-band component powertests

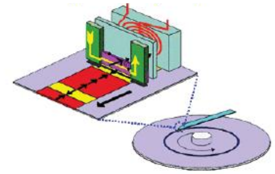
Design report

PDF at

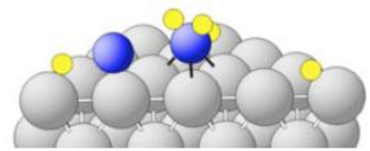
www.psi.ch/SwissFEL

SwissFEL Science Case

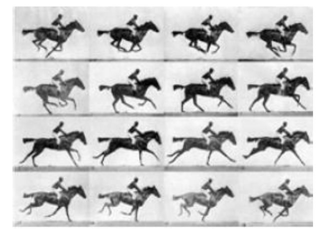
Magnetism: materials and processes for tomorrow's information technology



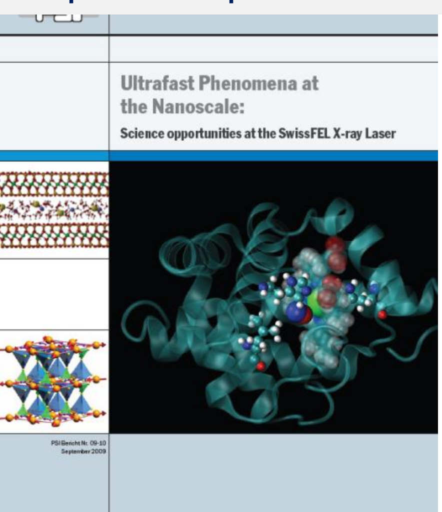
Catalysis and solution chemistry: for a clean environment and a sustainable energy supply



Coherent diffraction: flash photography of matter



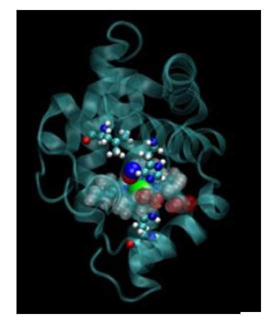
PDF of science report at
http://www.psi.ch/swissfel



Ultrafast Phenomena at the Nanoscale:
Science opportunities at the SwissFEL X-ray Laser

PSI Bericht Nr. 09-10
September 2009

Biochemistry:
shedding light on the processes of life



Correlated electrons:
the fascination of new materials